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22IEM05 NEWSTAND New calibration standards and methods for radiometry and photometry after phaseout of incandescent lamps

22IEM06 S-CALe Up Self-calibrating photodiodes for UV and exploitation of induced junction technology

22IEM07 INFOTherm Integrated European research, calibration and testing infrastructure for fibre-optic thermometry

22NRM01 TraMeXI Traceability in medical X-ray imaging dosimetry

22NRM02 STANBC Standardisation of Black Carbon aerosol metrics for air quality and

22NRM03 MetHyTrucks Metrology to support standardisation of hydrogen fuel sampling for

22NRM04 e-TRENY Metrology support for enhanced energy efficiency in DC transportation systems

22NRM05 MeLiDos Metrology for wearable light loggers and optical radiation dosimeters

22NRM06 ADMIT Characterisation of AC and DC MV instrument transformers in extended

22NRM07 GuideRadPROS Harmonisation, update and implementation of standards related to radiation protection dosimeters for photon radiation

22RPT01 TraInd BVK-H Traceability for indentation measurements in Brinell-Vickers-Knoop hardness

22RPT02 True8DIGIT Towards a true 8-digit digitiser

22RPT03 MultiFixRad Improving the realisation of the kelvin by multiple fixed-point radiation thermometry

22RPT04 RFMicrowave2 Development of RF and microwave metrology capability II

23CBC01 CaBuCo Capacity building coordination

23FUN01 PhoQuS-T Photonic and quantum sensors for practical integrated primary

23FUN02 CoCoRICO Controlled confinement to reduce the inaccuracy of clocks based on

23FUN03 HIOC High-accuracy ion-based optical clocks

23FUN04 COMOMET Fundamental physical metrology with cold molecules

23FUN05 AQuanteC Advanced quantum technology for metrology of electrical currents

23FUN06 ProMET Fundamental protein metrology to support the definition of

23FUN07 QuAHMET Quantum anomalous Hall effect materials and devices for metrology

23FUN08 MetSuperQ Metrology for superconducting qubits

23IND01 ENSURE Electric energy and supply reliability

23IND02 COMET Manufacturing of commutable calibrators and quality control materials

23IND03 RF 4 6G RF key quantities for 6G development

23IND04 MetSuperCap Metrology for static and dynamic characterisation of supercapacitors

23IND05 H2FlowTrace Flow measurement traceability for hydrogen in gas networks

23IND06 Met4EVCS Metrology for electric vehicle charging systems

23IND07 RadonNET Radon metrology: Sensor networks for large buildings and future cities

23IND08 DI-Vision Traceable machine vision systems for digital industrial applications

23IND09 MaritimeMET Metrology for green maritime shipping: Emission control through

23IND10 OnMicro On-wafer microwave metrology for future industrial applications

23IND11 ThermoSI Thermometry with embedded SI traceability for industrial applications

23IND12 ADAM Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing

23IND13 ScreenFood Metrology for food safety in the circular economy: targeted and

23IND14 xDDiff Multidimensional optical diffusion for the measurement of appearance

23NRM01 SBS Uncert Support for standardisation of sample-by-sample waveform uncertainty computation

23NRM02 SMURFnano Standardised measurements of surface functionalities on nanoparticles

23NRM03 BioAirMet Standardisation of bioaerosol monitoring for air quality and climate

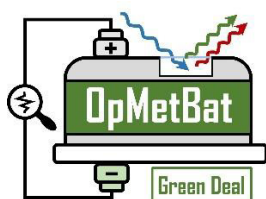
23NRM04 NoQTeS Normating colour-centre-based quantum sensing technology towards industrial application and standards

23NRM05 SensMonCT II Advanced detail sensitivity monitoring by new concepts to improve the

23RPT01 WAC Wideband AC quantum traceability

23RPT02 ETraceAbs Establishing European traceability for medical measuring devices

23RPT03 GrainMet Metrology for standardised moisture / water content measurements in plant-origin bulk materials in support of International and European food safety and trade



Publishable Summary for 21GRD01 OpMetBat Operando metrology for energy storage materials

Overview

The development of new battery materials is key to improving the performance, lifetime, safety and cost of energy storage technologies such as Li-ion batteries for electric vehicles. However, innovation is hampered by the inability of industry to reliably characterise their structure and chemistry in an operating environment. This project will build a metrological framework supporting traceable *operando* characterisation of state-of-the-art battery materials under dynamic charge / discharge conditions. This includes advancement and validation of *ex-situ* methods, establishing new protocols, cells and a best practice guide for *operando* approaches and developing new instrumentation enabling hybrid, multiparameter measurement to inform new materials development.

Need

The European Green Deal targets net zero CO₂ emissions of greenhouse gases in Europe by 2050, specifying zero emissions from new cars by 2035. Electrification of the automotive industry is key to meeting these goals, but rapid advances in energy storage technologies such as lithium-ion batteries are required to realise this. Many new materials combinations for battery electrodes are emerging that can begin to address performance targets, but lifetime issues remain problematic. Hence, there is an urgent need for traceable analytical techniques to decipher structure-behaviour relationships and elucidate degradation and failure mechanisms to improve battery performance by design, rather than empirically.

Quantification of elemental composition, and determination of oxidation and chemical binding states, coordination and phase structure are crucial for an enhanced understanding of battery electrode degradation (Objective 1). Moreover, investigations must be conducted in real-time, allowing aging mechanisms to be linked to battery state of charge (SoC) and state of health (SoH). Currently, degradation studies are performed *post-mortem*, using *ex-situ* methods where the cell is disassembled, leading to chemical modification which can distort the result. To avoid that, *operando* methods, where electrode materials are characterised simultaneously during cell charge-discharge, are needed. Whilst some *operando* methods are available, they are not sufficiently reliable or quantitative to allow confident data interpretation (Objective 2). Moreover, there is a need for new hybrid *operando* methods, where multiple measurands are synchronously probed during electrochemical cycling, to establish causal links between materials properties and their impact on cell performance (Objectives 3 and 4). Such advanced measurements bring new challenges as they require special sample environments such as dedicated electrochemical cells with thin probing windows, while ensuring that the electrochemical behaviour remains unperturbed. Hence, there is a need for establishing a robust, validated metrological framework for *operando* metrology, that can be transferred to battery developers and demonstrated through industrial case studies.

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: July 2024

Objectives

The project aims to develop *operando* techniques and hybrid (multi-modal) instrumentation, supported by quantitative and validated *ex-situ* analysis and electrochemical measurement methods, to enable beyond state-of-the-art materials characterisation for high-capacity energy storage technologies.

The specific objectives are:

1. To develop traceable chemical, physical and structural analysis methods for *ex-situ* characterisation of high-capacity energy storage materials (e.g. Li-ion and Li-S) and components (e.g. Cobalt, Nickel, Manganese) with a focus on x-ray spectroscopic techniques. This includes the fabrication and qualification of at least 3 calibration samples and verification by interlaboratory studies (post-mortem). A relative uncertainty in elemental composition determined by XRS of below 10 % will be targeted.
2. To establish a Good Practice Guide for current and emerging in *operando* spectroscopy methods including X-ray and vibrational spectroscopy, validated by *ex-situ* analysis and round robin tests, in order to establish and, where possible improve, experimental repeatability and accuracy with respect to elemental and species analysis of battery materials. In addition, to develop measurement protocols to assess the influence of cell geometry, electrode configuration, and measurement parameters on observable phenomena, as well as to assess the extent and influence of vacuum ultra-violet (VUV) or X-ray radiation damage.
3. To develop novel dynamic electrochemical approaches combined with in *operando* spectroscopy and dimensional metrology for the correlative assessment of the relationships between material structure and cell performances.
4. Based on the results of Objectives 1-3, to develop novel in *operando* instrumentation and hybrid methodologies for multi-parameter spectro-electrochemical characterisation of materials and components for high-capacity energy storage (e.g. in Li-ion and Li-S battery systems). To investigate the causal relationship between electronic/molecular- and microstructure information and charge carrier dynamics as measured with electroanalytical methods, to gain information on the state of health and state of charge.
5. To facilitate – in cooperation with the EMPIR JRP 20NET01 Clean Energy – the take up of the data and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, calibration laboratories), standards developing organisations (e.g. ISO/TC 201) and key end users (materials suppliers and battery manufacturers). To promote technology transfer of the project outputs as lab-based alternatives to synchrotron radiation-based methods, towards industry and manufacturers.

Progress beyond the state of the art and results

Traceable ex-situ characterisation of high-capacity energy storage materials (objective 1):

Despite a variety of existing approaches to *operando* characterisation of energy storage materials based on X-ray spectrometry, vibrational spectroscopy and X-ray diffraction, practices vary substantially across academia and industry. There is little agreement and consistency in terms of electrochemical cell geometry, materials handling methods and measurement protocols, leading to a lack of confidence in data comparison.

This project aims to make progress beyond state of the art by establishing a foundation for *traceable* and quantitative *operando* measurement built on *ex-situ* methods that are validated by adopting appropriate reference materials, calibration specimens or standardised procedures. Methods have been developed to characterise pristine NMC cathodes for Li-ion batteries using analytical techniques such as X-ray absorption spectroscopy (XANES, EXAFS and XRF), X-ray diffraction, X-ray photoelectron spectroscopy (XPS), Raman spectroscopy and secondary ion mass spectrometry (SIMS). XRF, XPS and SIMS measurements have provided information on the elemental composition (depth profile or at surface), and the measurement of fundamental parameters (e.g. absolute mass attenuation coefficients) with reduced uncertainties allows XRF measurements to be traceable to the international system of units (SI). XANES has enabled determination of the oxidation states of compounds and complements XES experiments with respect to revealing the entire electronic structure, while EXAFS measurements have given the interatomic distances to neighbouring atoms, in excellent agreement with the rather long-range order XRD studies. Moreover, the crystalline structure of the cathode material unveiled by XRD investigations by partners was used as an input to the theoretical

calculations of its electronic structure. The new Li-S battery system developed within this consortium is now operational and has been studied by the same techniques as for the Li-ion with NMC662 cathode.

Good practice guide for current operando spectroscopy and diffraction methods (objective 2):

For the first time, this project will develop and disseminate a good practice guide in the application of *operando* X-ray and optical techniques such as Raman spectroscopy. This will be achieved by developing cells and protocols validated by physical modelling, performing parametric studies to optimise experimental conditions, and undertaking interlaboratory comparisons to establish the root of uncertainties to improve experimental repeatability.

Various *operando* cell designs for use with different spectroscopic techniques have been discussed among partners (NPL, HZB, PTB, ULiv, ELECTRO) and two of these designs have been taken forward to the manufacturing stage. Electrochemical tests on cells assembled using a Li-ion full cell arrangement (NMC622/graphite) indicate that these *operando* cells can reliably be charged/discharged well over 50 times over the course of several weeks. The electrochemical cycling performance of the *operando* cells has been measured using rate capability tests and performance has been shown to compare well against conventional coin cells, indicating that the presence of the spectroscopic window has minimal effect on the electrochemical characteristics of the cell. Modelling has also been performed to show that small modifications to the internal geometry of the cell has limited effect on the electrochemical environment within the cell.

Measurement procedures have been established for using *operando* cells to characterise battery materials using Raman spectroscopy, XRS and XRD. This includes measurements to establish thresholds for sample damage caused by the laser or X-ray beam used in these techniques. In addition to analysis of the benchmark Li-ion chemistry, *operando* XRS measurements using calibrated instrumentation have been performed on the latest Li-S materials produced by UNIROMA1, which have revealed some interesting insights into the reversibility of the Li-S chemistry.

Novel dynamic electrochemical analysis approaches for combination with operando spectroscopy and dimensional metrology (objective 3):

HZB, NPL, UNIROMA1, PTB, ELECTRO, ULiv and WWU has made significant progress in developing and refining a battery impedance simulator. This instrument is crucial for accurately analyzing spectroscopy data as it accounts for correcting time drift as part of our innovative approach to dynamic electrochemical spectroscopy. The focus has been on developing a device that not only fulfils the technical specifications but is also user-friendly, taking into account feedback from all partners to improve usability and performance.

Notable progress includes HZB's leading role in developing the simulator, ensuring that it adheres to the detailed specifications and incorporates collective insights for excellent operation. Initial evaluations comparing the simulator's measurements with calibrated resistors have emphasized our commitment to traceability and precision. These careful tests and optimization measures underline our commitment to further developing this important device. The collaboration with NPL was crucial as they assisted in developing the simulator, particularly with the voltage/resistance measurement uncertainties and drift correction algorithms. Their contribution was decisive in the evaluation of the application of the simulator on coin cells. Similarly, UNIROMA1's involvement in the impedance discussions and PTB's expertise in accurate measurements contributed significantly to our project's scientific integrity and technical depth. The collaborative nature of the project was also demonstrated by ULiv's proactive steps in procuring additional test equipment and ELECTRO's role in combining technical fabrication and electrochemical acumen. HZB took the lead in documenting the design and implementation strategies, culminating in a comprehensive report for EURAMET. This report symbolizes the participants joint achievements and sets the course for further progress.

The project also focussed on refining the measurement script for electrochemical impedance spectroscopy (EIS). This endeavour aimed to improve the accuracy of battery performance analysis by addressing operational subtleties to ensure the script's compatibility and effectiveness with different devices. The development of this script, in conjunction with the generation and analysis of synthetic EIS data, represents a significant leap forward in the ability to simulate and correct operational drift accurately. In parallel, the projects study of Li-ion batteries is progressing through combined operational EIS and XRS techniques, with PTB improving its equipment for integrated measurements and partners such as ULiv and UNIROMA1 securing important beam time for operational XAS. This collective effort will deepen the understanding of Li-ion battery technologies and demonstrate our commitment to pioneering advances in battery analysis through innovative spectroscopic methods.

Novel operando instrumentation and hybrid methodologies for multi-parameter characterisation (objective 4):

Finally, the new knowledge generated throughout the project will be built upon to develop novel *operando* instrumentation and methodologies that further extend the state of the art by: (i) improving sensitivity compared to current approaches by developing new *operando* cell windows; (ii) allowing advanced X-ray methods normally confined to synchrotrons to be transferred to laboratory-based instrumentation; and (iii) enabling simultaneous, *hybrid*, multiparameter measurement to allow causal links between materials property changes to be established, and their links to cell performance loss to be identified unequivocally.

Regarding the further development of new cell design and window materials for traceable *operando*, multimodal or hybrid analytical and dimensional measurements several activities have been undertaken: HZB has successfully designed and provided multimodal *operando* analysis cells to its own labs, UNIROMA1, NPL, PTB, and ULiv. Furthermore, HZB already proposed an improved cell design based on the valuable suggestions received from all partners. The improved cells, already up-taken and manufactured by EMPA, feature a larger solid angle of acceptance allowing for X-ray and Raman experiments. OG, HZB and INRIM have successfully produced and delivered novel *operando*-cell window materials. These have been characterised using XRS by PTB, Raman by INRIM and AFM by CMI. JSI and TUB have further improved the ab-initio simulation tool for XES spectra. TUB conducted sensitivity calculations for laboratory and synchrotron XES equipment, which can be applied to any dispersive spectrometer with known detection angle and incident photon flux. JSI provided DFT calculations of Mn valence-to-core XES spectra. A quantitative investigation of the formation of soluble polysulfides in Li-S batteries with C/S composite electrodes (UNIROMA1) was carried out through an *operando* study spanning several synchrotron beamtimes (PTB).

The new framework for *operando* metrology is to be demonstrated by means of several industrial case studies, in which the tools developed shall be combined to deconvolute some of the most challenging degradation mechanisms. Such degradation is currently observed by battery developers and that can often not be resolved by current *ex-situ* characterisation techniques. For this reason, the Fiat Research Center S.C.p.A. (CRF) affiliate of the large automotive manufacturer Stellantis will carry out industrial impact case studies that will demonstrate how *operando* and *hybrid* characterisation techniques can overcome these issues. From an industrial perspective, regarding both R&D and quality management, the intended demonstration of transferability from large-scale facilities into the laboratory is highly desirable. One of the case studies led by CRF has been introduced to the Stakeholder Committee to provoke interest and seek specific challenges of relevance. The CRF study is focused on the comprehension of degradation mechanisms of commercial Li-ion cells for automotive applications; a disassembly laboratory protocol was setup to collect cathode, anode and electrolyte materials. Then these materials will undergo extensive chemical, physical and structural characterisation by *ex-situ* techniques, to compare results with newly developed metrology.

A new industrial collaborator has expressed interest in assessing electrolyte additives with respect to SEI modifications in NMC batteries under operation conditions which will be included in another case study. For all the industrial case studies intended, the traceable *operando* methods already applied to the novel Li-S systems may be extended to commercial battery chemistries without the need for any substantial changes.

Outcomes and impact

The following dissemination activities have been undertaken so far:

- 4 open-access peer reviewed publications and 3 dataset published in Zenodo repository
- Organizing dedicated session at international conferences (IWES 2024 and EMRS ALTECH)
- 8 training course/workshop/seminar for external (PTB, INRiM, UNG and UniRoma1)
- partners provided inputs to 10 standardisation committees
- 8 members of Stakeholder Committee from across industry and academia
- 22 presentations to international conferences / workshops / congresses

The first one of the four peer-reviewed papers one is a review concerning the selective infiltration of metals into nanostructured polymers. This process is generating interest in the development of optically-transparent window decorated with plasmonically-active nanostructures for *operando* surface enhanced Raman spectroscopy. The second paper focuses on determining the x-ray scattering coefficients for nickel being

crucial for accurate X-ray analysis. The third paper underlines that the accurate X-ray fluorescence analysis relies on good knowledge of the excitation source's spectral distribution. The study demonstrates the feasibility of a reference-free XRF method using polychromatic X-rays. The fourth paper is about the realization of nano-structured reference samples based on self-assembling block copolymer. Here a hybrid metrology strategy offers comprehensive material characterization and insights into nanoscale properties and functionalities.

Outcomes for industrial and other user communities

Through various dissemination activities, the protocols and best practice guidance established for the implementation of *operando* X-ray spectroscopy, Raman spectroscopy and X-ray diffraction for energy storage materials characterisation will be adopted by battery manufacturers (e.g. VW, Tesla, CATL) and user communities in Europe (e.g. European Battery Alliance, Battery European Partnership Association, Battery 2030+). The uptake of the good practice guide by battery and materials developers will add value to their materials characterisation. The EIS measurement protocol will be an ideal tool to access valuable information about processes in operating industrial cells, at low cost. In the first 18 months different *operando* experiments and related ex-situ experiments on various battery materials were conducted in view of analytical discrimination and sensitivity capabilities. The BIG-MAP project showed interest to co-work on the standardisation of battery materials and procedures. A UK SME battery developer joined the stakeholder committee.

Outcomes for the metrology and scientific communities

The good practice guide developed will benefit the scientific community by improving reliability, reproducibility, and fidelity of *operando* measurements. By encouraging the uptake of a common set of measurement protocols, the comparability of data across the literature will be greatly improved, allowing more conclusive links between materials chemistry/structure and behaviour. The consortium develops cells for *operando* and *hybrid* (multimodal) spectroscopy. The project will pioneer *operando* metrology for battery research at several European synchrotron radiation facilities and the transfer into laboratories to support industry and researchers.

Outcomes for relevant standards

The NMI participants are involved in key international organisations (ISO, BIPM, EURAMET). The most relevant standards committee is ISO TC201 with subcommittees on Raman and x-ray spectroscopies. The consortium will engage with VAMAS on the topics of Raman spectroscopy (TWA 42) and surface chemical analysis (TWA 2). INRIM provided a general presentation the consortium activities at the VAMAS Steering Committee in 2023. NPL attended two BIPM CCQM EAWG meetings in 2023 and presented the OpMetBat project. PTB introduced the project at the ISO TC201 SC10 meeting in 2023. A new sub-group within ISO TC201 (SG2) has been initiated on the topic of metrology for energy materials. SG2 compiled expert inputs in the fields of batteries, photovoltaics and other renewable energy sources and held its first technical meeting in 2023, chaired by PTB. Regarding OpMetBat discussions were held within the Battery European Partnership Association (BEPA) regarding standardisation that is crucial for advancing battery technology and metrology.

Longer-term economic, social and environmental impacts

The transition to hybrid electric vehicles is essential to reduce human impact on air pollution, global warming, and their effects on public health. Improved confidence in measurement is key to the development of next generation energy storage materials with sufficient performance and lifetime for automotive applications, and therefore underpins this energy transition. The methodologies under development, validation or application in OpMetBat were compiled for the strategic research agenda of the JNP on 'clean energy' that became an European Metrology Network (EMN) on 'clean energy' by February 2024.

List of publications

1) Irdi Murataj, Eleonora Cara, Nicoletta Baglieri, Candido Fabrizio Pirri, Natascia De Leo, Federico Ferrarese Lupi, "*Liquid Phase Infiltration of Block Copolymers*" *Polymers*, 14, 20, 4317 (2022).
<https://doi.org/10.3390/polym14204317>

2) André Wählich, Malte Wansleben, Jan Weser, Christian Stadelhoff, Ina Holfelder, Yves Kayser, Burkhard Beckhoff "*Experimental determination of differential scattering coefficients for nickel by means of linearly polarized x-ray radiation*" *Metrologia* 60, 3 035001, (2023). <https://doi.org/10.1088/1681-7575/acca87>

3) André Wählich, Malte Wansleben, Rainer Unterumsberger, Yves Kayser, Burkhard Beckhof “*Reference-free X-ray fluorescence analysis using well-known polychromatic synchrotron radiation*” J. Anal. At. Spectrom. 38, 1865-1873 (2023). <https://doi.org/10.1039/D3JA00109A>

4) Angelo Angelini, Eleonora Cara, Samuele Porro, Burkhard Beckhoff, Yves Kayser, Philipp Hönicke, Richard Ciesielski, Christian Gollwitzer, Victor Soltwisch, Francesc Perez-Murano, Marta Fernandez-Regulez, Stefano Carignano, Luca Boarino, Micaela Castellino, Federico Ferrarese Lupi “*Hybrid Metrology for Nanostructured Optical Metasurfaces*” ACS Appl. Mater. Interfaces 15, 50, 57992–58002 (2023). <https://doi.org/10.1021/acsami.3c13923>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01.09.2022, 36 months
Coordinator: Burkhard Beckhoff, PTB Tel: +49 30 34817170 E-mail: Burkhard.Beckhoff@ptb.de Project website address: https://opmetbat.inrim.it/		
Internal Beneficiaries: 1. PTB, Germany 2. CEA, France 3. CMI, Czechia 4. INRIM, Italy	External Beneficiaries: 5. CRF, Italy 6. HZB, Germany 7. JSI, Slovenia 8. MEU, Türkiye 9. TUB, Germany 10. UNG, Slovenia 11. UNIROMA1, Italy 12. WWU, Germany	Unfunded Beneficiaries: 13. OG, Germany
Associated Partners: 14. ELECTRO, United Kingdom, 15. Empa, Switzerland, 16. JM, United Kingdom, 17. NPL, United Kingdom, 18. Uliv, United Kingdom		
RMG1: INRIM, Italy (Employing organisation); PTB, Germany (Guestworking organisation)		

*JM ceased participation on 01 November 2022



Publishable Summary for 21GRD02 BIOSPHERE

Metrology for Earth Biosphere: Cosmic rays, ultraviolet radiation and fragility of ozone shield

Overview

One of the most significant – yet unexplored – ecological challenges facing EU member states and beyond is the impact on human and environmental health of the increasing atmospheric ionisation caused by extra-terrestrial radiation (cosmic rays and solar UV radiation) boosted by anthropogenic emissions. This project aims to develop the necessary tools, methodologies and measurement infrastructure needed to evaluate the mutual impact of cosmic rays and biologically active UV radiation on the Earth's biosphere, and to support EU policy makers with scientific assessments and information that have the potential to substantially improve policies on climate, health and anthropogenic emission activities.

Need

Cosmic rays, along with UV radiation and the Earth's natural radioactivity, are one of the main sources of atmospheric ionisation, contributing to the electrification of the lower atmosphere and, thus, to the climate system in general. Attempts to quantify the changes this radiation causes in climate processes (e.g., cloud formation and thunderstorms), however, are debated and remain poorly understood. Over millennia, living organisms have been continuously exposed to cosmic rays and solar UV radiation. Biological actions of many kinds have evolved to deal with such exposures and a balance between beneficial and harmful effects of these radiation fields has been established. In recent years, however, this balance has been disturbed due to anthropogenic (man-made) emissions and environmental pollution creating an urgent need to study how these combined radiation fields are shaping our natural habitat, affecting the evolution of the biosphere, and impacting on our health. To achieve this, a combination of observations is needed using modern satellite technologies and ground-based *in situ* and remote sensing in environmental biology, chemistry and also radiation protection, to start the evaluation of cosmic and solar radiation effects on the biosphere.

Ionisation of the biosphere by cosmic radiation is known to correlate significantly with disease prevalence in humans, infectious disease mortality, and overall mortality. This is in addition to the harmful effects caused by UV radiation alone, which increases the incidence of skin cancer by about 2 % for every one percent reduction in ozone. Genomic, epigenetic, transcriptomic, and metabolomic changes potentially responsible for cellular radio-sensitivity and possible long-term dysfunction remain, however, largely unknown. The lack of understanding of these effects is exacerbated further by ozone depletion-induced overexposure to UV radiation and its implications for cellular defence mechanisms. Therefore, monitoring, modelling, and correlating cosmic rays, terrestrial solar radiation, and ozone thickness is critical not only to understand the radiological sensitivity of cells, but also to make informed decisions regarding the global challenges facing our society.

Traceable metrological data on cosmic ray fluxes, solar UV spectra, and the total ozone column are key to assessing the role of cosmic rays as climate drivers but quantification of correlations between them is required to inform new approaches to chemistry-climate models that will help clarify current ambiguities in the scientific community related to climate variability. Cosmic rays entering the top of the Earth's atmosphere, or primary cosmic rays (PCR), interact with atmospheric constituents to produce secondary cosmic rays (SCR), which are measured by ground-based instruments. The generation of an improved understanding of the role of PCR and SCR in ozone depletion, would provide a better assessment of biological implications due to natural UV overexposure. Quantification of ionisation and the production rates of charged molecular fragments and other reactive species is needed to extend present-day models that are currently limited to ionisation and the

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PU – Public, fully open

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European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: June 2024

nonspecific energy loss values required to produce an ion pair. The interaction cross sections for these processes need to be examined and measured experimentally to improve the reliability of the ionisation data of natural atmospheric and anthropogenic gases relevant to ozone layer chemistry. Implementation of these cross sections into simulation codes for space radiation propagating through the atmosphere leads to refined radical, ion and slow electron production rates, which are needed to enable a more accurate estimation of the effectiveness of the cosmic ray model compared to the photochemical model in depleting the ozone layer. This is important for predicting future trends in ozone hole dynamics and for assessing the role of new chemicals in the ozone depletion.

Therefore, it is necessary to identify and quantify the relationship between cosmic radiation, ozone depletion and anthropogenic emission with the help of simultaneous modelling and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column (Objective 2). To achieve this, this project will characterise and calibrate novel SCR instrumentation – including an upgraded LIDAR system. Since generation and decay of SCR depend on air density, knowledge of atmospheric profile parameters such as temperature, density, and aerosols are needed to establish an accurate relationship between SCR and PCR fluxes (Objective 1). For the first time, this project will determine fundamental data on the interaction of low-energy cosmic-ray induced electrons with atmospheric gases of both natural and anthropogenic origin (Objective 3). This includes collision cross sections for the molecular processes such as dissociative electron attachment, molecular fragmentation and ionisation needed for the evaluation of mitigation strategies for the effects of anthropogenic emissions for the greater protection of human, animal and ecological health, and the development of policies that support these strategies. The impact of combined cosmic and UV irradiation on human health will be assessed by investigating structural and functional damages inflicted by such mixed radiation fields in human normal cells such as primary skin fibroblasts and keratinocytes, blood monocytes and lymphocytes and endothelial cells (Objective 4). Genomic, epigenetic, and transcriptomic changes that might be responsible for cell radiosensitivity and possible long-term dysfunction will be assessed, in this project, in connection with the fate of irradiated cells in terms of viability, morphology and functions.

Objectives

The overall aim of this project is to develop metrological methodologies to establish the correlations between primary and secondary cosmic rays (PCR and SCR), solar UV radiation and ozone layer thickness, and to assess their mutual impact on the Earth's biosphere.

The specific objectives of this project are:

1. To determine the dependence of SCR on PCR and atmospheric parameters (e.g., temperature, density, aerosol concentration), based on field measurements made using well characterised and traceable modified mobile SCR muon and neutron detectors, a novel semiconductor detector and adapted and/or existing LIDAR systems for vertical atmospheric profiling.
2. To identify and quantify the correlation between PCR and solar UV radiation on the ground including their dependence on anthropogenic gas emissions using simulations and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column.
3. To determine the molecular processes affecting ozone depletion and atmospheric dynamics, and to provide a complete database of collision cross-sections for natural atmospheric and anthropogenic gases. This is to be based on simulations and experimental validations that quantify molecular ionisation (absolute ionisation, excitation, dissociation cross section energies and projectile energy loss) and production rates of charged molecular fragments of both natural and anthropogenic atmospheric gases including CFCs and CH_2Cl_2 from interactions with low and medium energy (<10 eV - 2000 eV) electrons.
4. To assess the potential effect on human health from exposure at environmental levels to combined SCR and UV radiation fields using healthy human cell lines. This is to be based on simulating environmental level exposures under experimental conditions to establish correlations between radiation type and flux, and changes to cellular parameters (cell death, DNA damage and genomic instability, adhesion, and proliferation). In addition, to determine the expression profile of stress genes using established radiation effect models and systems biology approaches.

5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs and DIs, atmospheric monitoring networks), standards developing organisations (e.g. IEC, ISO, CENELEC, CCRI (I) and EURAMET Technical Committee for Ionising Radiation (TC-IR)) and end users (e.g., health and environment regulatory bodies, research institutions focused on environment, climate, medicine and biology, and radiological protection, and instrument manufacturers).

Progress beyond the state of the art and results

Cosmic ray-induced low energy electrons and solar UV radiation are major drivers for atmospheric chemistry. For quantitative description of atmospheric ionisation, interactions with anthropogenic gases, collision and chemical processes involving ozone, climate-chemistry models require reliable cross-sections for the interactions of gases in the stratosphere with low energy electrons as well as for the production of reactive species by those interactions. This project will determine for the first time the medium to low-energy electrons cross sections for ionisation and fragmentation-ion production of atmospheric constituents such as N₂, O₂, NO, NO₂, selected chlorofluorocarbons (CFCs), halogenated molecules (such as HCl, HF, HBr, SF₆), as well as aromatic and nitrogenated molecules (such as pyridines whose cations facilitate aerosol formation).

Objective 1: Determining the dependence of SCR on PCR and atmospheric parameters

The SCR flux measured at ground level is affected by the survival probability of the incoming parent PCR particles, the various atmospheric conditions such as air density and temperature, and the particle absorption rate down this path. Corrections which exploit the exponential dependence of pressure or temperature on altitude are currently used for these effects, but these do not consider the inhomogeneities of air density that affect the accuracy of the recorded SCR fluxes. This project will develop, for the first time, metrological methods to quantify the correlation between PCR and SCR using atmospheric profile parameters measured by LIDAR(s). These will include a novel mobile scintillator-based muon detector capable of measuring muon flux reaching the ground level with an energy distribution from a few hundred MeV to a few hundred GeV, a novel boron scintillator-based mobile neutron detector which can measure neutrons in a wide range of energies (from thermal up to several tens of MeV), and a spectral-tracking particle telescope assembled as stack array from 2 semiconductor pixel detectors (Timepix3) in miniaturised and portable architecture for high-angular resolution wide field-of-view mapping of SCR with resolving power of mixed-field components (muon, electron, proton, ion, gamma, X ray, neutron).

The function and light collection efficiency of the mobile muon detector has been characterized with ⁹⁰Sr beta source. The performance of the detector with ambient radiation and with photon gamma reference fields (⁶⁰Co and ¹³⁷Cs) has been commissioned. Data processing and analysis algorithm to obtain muon fluxed have been developed. The inherent background was investigated and determined at the PTB's underground laboratory, while the calibration with respect to ambient dose equivalent rate and muon flux was performed at the PTB's environmental dosimetry site (ERADOS). Performance tests were also carried out at ERADOS, and the results were compared with PTB's reference instrument, which continuously measures charged component of SCR.

The mobile neutron detector system was characterized and calibrated at the CMI in different reference fields for photons (¹³⁷Cs, ⁶⁰Co, X-rays 40-300 kVp) and neutrons (AmBe, Cf, thermal neutrons) to determine the neutron component of the SCR. Performance tests were carried out at the Lomnický Štít High Altitude Observatory (Slovakia) and the results were compared with those of the SEVAN detector, which continuously measures cosmic rays.

Two high-resolution particle telescopes consisting of two Timepix3 pixel detectors arranged in close stacked architecture have been developed. One configuration (Configuration A) is Si Timepix3 (TPX3) 300 µm (top) and TPX3 Si 1000 µm (bottom), the other configuration (Configuration B) is TPX3 Si 500 µm (top) and TPX3 CdTe 2000 µm (bottom). The Timepix3 telescope tracker provides enhanced resolving power of radiation type decomposition for precise measurement and monitoring of the flux, composition, and direction of mixed radiation fields. The telescopes were tested and calibrated with proton and electron beams. The response of Timepix3 detectors with silicon and CdTe sensors to thermal and fast neutrons generated in well-defined reference radiation fields has been tested and evaluated in terms of radiation field visualization, flux, detection performance and neutron energy.

NTUA EOLE and Raymetrics lidar systems have been upgraded to meet BIOSPHERE requirements for measuring aerosol mass, atmospheric density, and temperature profiles. The NTUA EOLE lidar system provides the vertical profiles of the aerosol extinction and backscatter coefficients, as well as the aerosol mass

concentration (the latter only in aerosol-free atmospheric layers). The EOLE's detection range spans from 0.8 km to 25 km with a density accuracy up to 15%, mass concentration accuracy below 20 % and spatial resolution of 15 m (800 m height) and 200 m (25 km height). The temperature lidar system of Raymetrics SA is currently capable of detecting lidar signals at 5 channels (354.78nm, 387nm, 407nm and at two pure rotational Rama (PRR) channels (355.4 nm, 356.3 nm), the latter used to retrieve the atmospheric temperature profiles. The lidar system provides vertical temperature profiles from 300 m up to 8 km during daytime and up to 25 km during nighttime, under favorable meteorological conditions (e.g. no clouds, low aerosol content). The temperature resolution is 1 K while range resolution 70 m. In addition, the minimum and optimal measurement parameters, and the technical requirements for an optimal LIDAR system to determine the effects of atmospheric profiling parameters on the SCR flux to the ground were prospected. The mobile muon and neutron detectors and NTUA EOLE and Raymetrics SA LIDAR systems were operated simultaneously in the first measurement campaign (1 July to 31 August, 2023) at the NCSR-DEM station (near NTUA) in Athens, Greece.

Objective 2: Identifying and quantifying the relationship between cosmic radiation, UV radiation and anthropogenic emission

Side-by-side measurement of the terrestrial solar UV spectrum, total atmospheric ozone, and SCR flux rate has never been attempted so far due to the lack of the proper measurement framework. This project will provide such measurements for the first time and will go beyond the state of the art not only by measuring these parameters simultaneously, but also by supporting the ground-based measurements with satellite measurements such as satellite observations of energetic electron, proton and Helium-ion fluxes. Simultaneous measurement of SCR fluxes, UV radiation spectrum and ozone column, enabling a quantification of the relationship between them, will be carried out at four European sites (Greece, Belgium, Czechia, and Germany). This will provide the necessary infrastructure for an accurate measurement of atmospheric profiling parameters and have different anthropogenic emission inventories to integrate the influence of anthropogenic emissions on ozone dynamics.

The first measurement campaign took place at the National Center for Scientific Research (NCSR)-Demokritos (DEM) station in Athens between June 1, 2023, and August 31, 2023, using 10 instruments simultaneously: UVB pyranometer and GUV-511 multichannel filters radiometer, UV spectroradiometer BTS-Solar, ³He neutron detector, portable neutron detector system based on liquid scintillators, mobile muon detector based on plastic scintillators, CIMEL Sun photometer, EOLE Multiwavelength Raman LIDAR, DEPOLE Depolarization LIDAR and temperature/aerosol/density LIDAR. Correlations of SCR flux rates with atmospheric parameters such as pressure, temperature and relative humidity were identified. A comprehensive Monte Carlo simulation analysis of the cosmic muon flux and the energy spectra as a function of atmospheric parameters at different altitudes is currently being carried out.

The second measurement campaign took place at the urban Spacepole site in Brussels (Belgium) between 01.01.2024 and 31.03.2024. More than 10 instruments were used simultaneously: UVB pyranometer, GUV-511 multichannel filters radiometer and double monochromator for global solar UV irradiance measurements, UV spectroradiometer BTS-Solar for direct Sun irradiance measurements and total ozone column, ³He neutron detector, portable neutron detector system based on liquid scintillators, mobile muon detector based on plastic scintillators and portable gas-based muon detector. A CIMEL Sun photometer from BIRA-IASB for aerosols optical depth was also available. Royal Meteorological Institute of Belgium contributed with Brewer spectrophotometers measuring solar UV and total ozone column, LIDAR ceilometers measuring the backscattering signal by aerosols, fog and clouds, and performed balloon sounding to measure vertical profiles (ozone concentration and atmospheric parameters).

Objective 3: Molecular processes affecting ozone depletion and atmospheric dynamics

This project will produce for the first time a complete database of collision cross sections for natural atmospheric and anthropogenic gases relevant for ozone layer chemistry. The database will be in an open format and will also include the quantification of molecular ionisation and production rates of charged molecular fragments and other reactive species going beyond present-day models which restrict to ionisation and a nonspecific energy loss value per produced ion pair.

Fragmentation cross sections of several chlorofluorocarbons (CFCs) such as CHClF₂, CClF₃, CHClF₂, CF₄, CH₂F₂ and CH₃Cl have been measured with a reflectron time-of-flight (rTOF). Differential elastic scattering cross sections (DCS) of electrons on ethanol were experimentally determined for electron energies between 30 and 800 eV for scattering angles θ of 30° to 150° in steps of 15°. The experimental data were compared to

theoretical values calculated using the modified independent atomic model (MIAM) and the independent-atom method with screening-corrected additivity rule (IAM-SCAR). Absolute electron scattering cross sections and differential elastic scattering cross section on N_2O and, cross sections for collisions of superoxide ions (O_2^-) with CO_2 , NO_2 and NO were also measured (electron detachment cross sections –could be referred to as charge transfer cross sections instead, ionization cross sections). Ionization experiments were performed on the water cluster beam using an ion- and electron-momentum spectrometer. The data collected show that collisions with electrons can result in the disintegration of small water droplets in the atmosphere. Presently dissociative electron attachment measurements are conducted on CFC molecules.

Simulations using AtRIS Geant 4 code of the effects of the cosmic rays (primary and secondary), as well as solar energetic particle events, on the terrestrial atmosphere have been developed. The composition of the atmosphere, the geometry of the planet and the magnetic field model have been studied to determine their influence on the atmospheric dynamics. Cases of low and high solar activity levels, and Solar Energetic Particle events as observed by PROBA-V/EPT and GOES have been investigated to determine the long term and short-term variations of atmospheric ionization. The effects of solar protons on the flux variations in the terrestrial radiation belts observed from 2013 to mid-2023 have been investigated and published. The atmospheric influence (seasonal periodicity, solar activity and composition variability) on cosmic ray induced ionization and absorbed dose rates has been determined. Time variability of ozone density has started to be studied using Copernicus Atmosphere Monitoring Service and MLS data. Ozone depletions during some major magnetospheric storms are being analysed.

A chamber for plasma generation has been commissioned using mixtures of N_2 and ozone gases in the 0.1 to 1 mbar pressure range and by optimization of the plasma parameters using a Langmuir probe. With suitable anode-cathode voltages, electron temperatures in the 10 eV range could be reached which is suitable to induce molecular reactions as they are expected for the cosmic ray secondary particles.

Objective 4: Effects of combined SCR and UV radiation fields on biological systems

Understanding the mutual impact of cosmic and ultraviolet radiation on human health is important not only for humans, but for all mammalian and plant species and the entire living ecosystem. This project will go beyond the state of the art by creating, for the first time, a database of results from irradiated and non-irradiated biological samples such as lung and primary skin fibroblasts, cerebral microvascular endothelial cells from the brain, and healthy blood monocytes. Through advanced bioinformatics and systems biology methodologies, a complex network of molecular changes related to cell death, DNA damage and genomic instability, adhesion and proliferation, and expression profile of stress genes will be established.

Experiments to assess the biological impact of a combined exposure of human normal proliferating CRL 9855 monocytes and primary lymphocytes (non-malignant) to SCR (energetic protons) and UVB radiation, in terms of cellular viability and proliferation, DNA damage and stress gene expression as measure of the cellular damages have been performed at the PTB Ion Accelerator Facility (PIAF) in July 2023. Human CRL 9855 monocytes were stored in liquid nitrogen. Lymphocytes were isolated from blood of healthy donors. Monocytes were unfrozen at PTB and were cultivated for 9 days to stabilize the cell culture and multiply the cells through passages at 2-3 days by adding fresh culture medium and periodic adjustment of cell concentration at 500000 cells/mL. CRL 9855 prepared for experimentation were then exposed to energetic protons (0.25 Gy and 0.5 Gy) followed within 15-20 min by exposure to UVB radiation in the range of fluences between 100 J/m² and 800 J/m². Unexposed cells (kept in the lab or in the irradiation room) and cells exposed only to protons or to UVB were considered as controls. In total, 9 exposure experiments were performed, 6 with 0.25 Gy protons and 3 with 0.5 Gy protons, combined with various UVB fluences, as described above. Part of the exposed cells and the corresponding controls were processed for assessing complex DNA damage, using the NTUA established gammaH2AX immunofluorescence methodology at post-irradiation times: T0 ('0' hrs), and part were further cultivated for 24 h at 37 °C to follow the response of cells to the specific stress. Cellular viability and proliferation were measured using the MTS reduction assay, while the rest of the cells were processed for evaluating the level of DNA damage and stress-response gene expression at 24 h. Processed samples were transferred to NTUA and IVB for final evaluation of DNA damage and stress gene expression. Preliminary results show a severe detrimental biological effect for UV radiations and synergy between protons and UV for the induction of cell death, decreased viability and chromosomal breaks.

Two complementary measurement campaigns at PIAF were performed in December 2023 and April 2024. Dose effects response curves were measured. Measurements towards lower dose values (0.1 Gy) were

started. Biological damage triggered in the irradiated cell lines have been measured. Primary endpoints to be used are complex in situ DNA damage, reproductive cell death (clonogenic survival) and chromosomal instability. In addition, and to investigate possible secondary effects of radiations, other cellular parameters will be investigated such as the type of cell death (immunofluorescence/flow cytometry).

Outcomes and impact

The advances of BIOSPHERE were presented at more than 30 national and international conferences and meetings. For more details, see <https://euramet-biosphere.eu/index.php/conferences-and-meetings>.

To communicate the objectives and results of the project in a non-technical/semi-technical language to increase interest in and awareness of the project's developments, 6 videos were produced, each covering one work package and published on YouTube: <https://www.youtube.com/watch?v=KpCipn-36mQ>, <https://www.youtube.com/watch?v=-9uHemppKtk>, https://www.youtube.com/watch?v=5NAr_YGlpQw, <https://www.youtube.com/watch?v=baSR-NoCRdw>, <https://www.youtube.com/watch?v=Ixui9CviKlk>, and <https://www.youtube.com/watch?v=WH6reSXWiik>.

Outcomes for industrial and other user communities

The project's data on the combined SCR and UV irradiation of human skin, blood and brain cells will be provided via databases accessible via our website to enable key information on a plethora of biological effects such as DNA damage, genome instability, cell death, oxidative stress, subtle structural changes and transcriptomic changes to be accessible. A registry with detailed list of biological samples, major protocols and reagents used in all experiments in the period July 2023 to April 2024 has been uploaded in the project website (<https://euramet-biosphere.eu/ProjectDir/Cells-reagents-and-protocols-BIOSPHERE-PROJECT.pdf>). A database which includes experiments with five different types of radiation, X-rays, γ -rays, protons, carbon ions and α -particles has been linked in our project website (<http://radbiodb.physics.ntua.gr/radphysbio/>). More specifically, it contains 2,734 experiments performed on human cells, and it combines the physical and biophysical properties of radiation while expressing the induced biological damage.

The cross-section data produced in this project are being currently published in peer-reviewed journals (see M. Dinger et al., <https://doi.org/10.1140/epjd/s10053-023-00632-6> and <https://doi.org/10.1103/PhysRevA.109.062813>). By February 2025 we expect to have the first version of the cross-section data base which will include the cross section data for all molecules measured in the project. These resource supports global atmosphere monitoring programmes and will also provide valuable input to chemistry-climate models.

Outcomes for the metrology and scientific communities

The methodologies developed in this project will help estimate the on-ground magnitude of cosmic events such as energetic Solar Particle Events (SPE) and Gamma Ray Bursts (GRB) and will provide information for designing biomedical studies for assessing the impact of radiation exposure on human health, in relation to radiation dose and dose rates. A Good Practice Guide for the simulation and estimation of particle fluxes during minimum solar activity, maximum solar activity and the recent Solar Energetic Particle Events has been drafted and published in the website. Please go to the project website to see the guide's initial draft and provide feedback on it (https://euramet-biosphere.eu/ProjectDir/Good_practice_guide_for_the_analysis_of_high_energy_trapped_particles_and_Simulation_of_their_Interaction_with_the_Atmosphere_measurements.pdf)

The new database of collision cross sections for natural atmospheric and anthropogenic gases will enable modellers, developers and end users to assess the role of low-energy cosmic electrons on the ozone depletion and atmospheric dynamics. The project's new database with results of irradiated and non-irradiated biological samples will enable modellers, developers and end users to assess the effects of combined SCR and UV radiation fields on human health.

Outcomes for relevant standards

The project will provide guidance for stakeholders and input to international standardisation bodies (ISO, IEC, CENELEC), for both ionising and non-ionising radiation protection via input to the following committees. Thus, the project will support the harmonisation of procedures and methods for the measurement of cosmic rays and

solar UV radiation in the environment and hence their inclusion into European and international standardisation.

Longer-term economic, social and environmental impacts

The objectives of the BIOSPHERE, including the operational capacity, needs and the impact, were presented at the Metrology for Climate Action 2022 that was organized by BIPM, WMO, and EURAMET and was held as an online workshop on 26-30 September 2022 (<https://www.bipmwmo22.org/>). During online sessions for recommendations on key technical challenge areas for metrology over the next decade, recommendations were given to WMO and BIPM workshop panel-chairs to investigate the need for and correct communities to support research into identifying and quantifying the relationship between cosmic radiation and ozone depletion and the impact this has on health and ecosystems. These recommendations were included in the workshop report that has been published on June 20, 2023 and is available on the BIPM website (<https://www.bipm.org/documents/20126/27085544/RapportBIPM-2023-03.pdf/57b00234-2bd0-09e1-8d4f-4aaed2ae45fd?version=2.4&t=1687244959519&download=true>).

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Project start date and duration:		1 October 2022, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	8. ADVACAM, Czechia	20. CSIC, Spain
2. BFKH, Hungary	9. BIRA-IASB, Belgium	21. GGO, Germany
3. CEA, France	10. DTU, Denmark	22. IRM, Belgium
4. CMI, Czechia	11. DWD, Germany	
5. GUM, Poland	12. IFIN-HH, Romania	
6. IMBiH, Bosnia and Herzegovina	13. IVB, Romania	
7. TUBITAK, Türkiye	14. LZH, Germany	
	15. MPG, Germany	
	16. NOVA, Portugal	
	17. NTUA, Greece	
	18. Raymetrics, Greece	
	19. UJF CAS, Czechia	

Publishable Summary for 21GRD03 PaRaMetriC

Metrological framework for passive radiative cooling technologies

Overview

Cooling systems account for nearly 20 % of electricity consumption and 10 % of greenhouse gas emissions, globally. With demand for cooling expected to grow tenfold by 2050, and the increasing frequency of extreme heat waves, improving the efficiency of cooling systems plays a critical role in addressing the global climate challenge. Passive Radiative Cooling (PRC) materials that can dissipate heat as infrared radiation have recently emerged. This project aims to develop a comprehensive metrological framework, including standardised performance indicators (i.e. figures of merit) and testing protocols, to enable the comparable evaluation of their cooling performance on-site and determination of the potential energy savings that could derive from the deployment of such technologies.

Need

The annual cost of heat-related issues is estimated at about \$2.4 trillion, with cooling systems costing an estimated \$300 billion and producing 1 Gt of CO₂ per year. By 2050, the additional energy needs related to cooling are expected to surpass the total electricity use of China and India today, combined. This is often referred to as one of the most critical blind spots in today's energy debate, given that the rising demand for cooling will add an enormous strain on the electricity systems of many countries, driving up emissions and triggering a self-aggravating feedback loop.

PRC materials can dissipate heat through the infrared transparency window (8 μm – 13 μm) without using any electricity, using outer space as a cold and renewable thermal energy sink to reach sub-ambient temperatures even under direct sunlight owing to their tailored optical and infrared photonic properties.

Despite hundreds of promising PRC coatings and devices demonstrated in the literature in the past few years, reliable testing protocols to evaluate their cooling performance have not been established yet, which is a major obstacle hindering the further development and commercialisation of this new technology. Typical tests up to now are limited to measuring either a temperature drop or cooling power with a heater, using improvised testing rigs with inconsistent insulation and shielding properties, unspecified thermal loads and under different atmospheric conditions, altitudes, ambient temperatures, etc.

Defining standardised figures and testing protocols requires the development of a new conceptual framework and a highly multidisciplinary approach improving both the modelling and the characterisation of emissivity and reflectance properties of thin coatings over a broad wavelength range, the realisation of benchmark systems with known properties, the calibration of portable instruments for on-site monitoring, as well as models accounting for the impact of atmospheric and geoclimatic conditions on the expected cooling potential and the design of standardised testing apparatuses with known thermal loads and insulation.

Objectives

The overall goal of this project is to establish a metrological framework for comparable performance assessments of passive radiative cooling technologies. The specific objectives of the project are:

1. To develop the conceptual framework for comparable performance assessments of passive radiative cooling technologies. This will include the preparation of candidate benchmark PRC materials and

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: May 2024

preliminary characterisation of their spectral responses, with a view to selecting a subset. Additionally, to define one or more figures of merit to assess the performance of PRC materials.

2. To develop and validate numerical models to correlate the cooling performance of PRC materials with the thermal and optical properties of their components, and thus to establish their specifications and associated tolerances. This will include carrying out the thermal infrared spectral modelling of the radiative exchanges between PRC materials, the atmosphere and space at different zenith angles for calculations of the net cooling power of the materials. Additionally, to evaluate the potential impact of PRC materials on energy savings and heat-island effect for urban environments in different climatic regions of Europe.
3. To develop accurate and traceable approaches for determining the thermophysical properties and thermal conductivity of PRC materials, and for converting measured radiometric quantities into a usable form for heat balance calculations. The reflectance and emittance will cover a broad spectral range (0.25 μm – 50 μm) encompassing the solar spectrum and the infrared transparency window of the atmosphere (8 μm – 13 μm). The target uncertainties will be below 3 % for emissivity and absorptivity, 5 % for the total hemispherical emissivity and below 10 % for the thermal conductivity.
4. To develop setups and protocols for on-site testing of PRC materials, with a target uncertainty below 10 % for the figures of merit.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (testing laboratories), standards developing organisations (CEN/ TC 89) and end users in the commercial and residential sectors.

Progress beyond the state of the art and results

Figures of merit tailored to passive radiative cooling materials and reproducible model systems

To date, figures of merit to evaluate the cooling performance of a PRC coating are either based on intrinsic material properties, the temperature difference between the substrate and ambient air, or the cooling power of the radiator at ambient temperature. All these quantities are severely affected by ambient, atmospheric and geoclimatic conditions, failing to predict cooling performances under different solar irradiance or relative humidity levels, or to differentiate between broadband and selective emitters. Other parameters typically used for traditional cool-roof applications, such as the Solar Reflectance Index, suffer from similar shortcomings as they were designed for a different class of materials.

The project partners have identified a list of figures of merit that have been used in the literature up to date, along with the relevant environmental parameters that should be monitored. The result of a comprehensive survey on the existing figures of merit, boundary conditions and comparison methods has been prepared and published as a public document on the project website and Zenodo (<https://doi.org/10.5281/zenodo.10260070>). The document has been shared with stakeholders and technical committees. Additionally, a set of at least three candidate benchmark materials has been identified, comprising materials with different surface finishes ranging from a perfect specular to a diffusely reflective behaviour. The consortium has secured a sufficient supply of these materials, including large scale samples. Even more materials are being tested by the consortium in collaboration with other stakeholders and collaborating institutes, aiming at scientific publications.

Multi-scale modelling of PRC composite materials

Modelling of PRC materials is a complex task involving several disciplines, numerical tools and length scales which span across several orders of magnitude in size, requiring research efforts beyond the reach of single institutes. Moreover, high-performing PRC materials are often hierarchical disordered materials, which is particularly challenging for numerical approaches often limited to 2D approximations.

Understanding the cooling performance of PRC materials requires modelling activities over multiple systems and scales. Numerical studies on the optical response of multi-layered materials in the solar and thermal infrared wavelength range revealed the impact of inevitable thickness fluctuations over the optical properties at short UV wavelengths. Different thermally insulating materials have also been evaluated numerically for the realisation of the sample test boxes, revealing common shortcomings with insufficient thickness or sunlight screening of the boxes found in the literature. Further modelling at system scale is ongoing to evaluate and compare the expected performance of different implementations of passive radiative cooling technologies in

the prototypes and for certain applications at the building scale. On an even larger scale, progress was made on the integration of different data sources and models for the calculation of downwelling atmospheric irradiance values at a certain time and location, resolved into spectral bands. Work is currently ongoing to include the effect of clouds (which can have different compositions based on their altitude), the effect of which is crucial to get realistic estimates of the average cooling potential associated to a certain region on a yearly basis.

Optical and thermal characterisation of thin, composite materials

Thermal characterisation of sub-mm composite coatings is particularly challenging for state-of-the-art methods used to measure thermal conductivity, such as the Guarded Hot Plate or Heat Flux Meter. More flexible, transient methods need to be examined and validated for this purpose. Similarly, routinely used methods to measure the emissivity of building materials rely on commercial instruments measuring directional emissivity values. However, heat balance calculations relevant to PRC materials require the total hemispherical emissivity, which must be either measured directly or extrapolated from directional measurements using validated methods. Similarly, the angular dependence of the emissivity of PRC devices needs to be evaluated to determine the best relative orientation between the radiating panels and the sky. The EMPIR project 16NRM06 EMIRIM, focused on the measurement of total hemispherical emissivity of the reflective foils used as the skin of thermal insulation products for buildings, demonstrated that the extrapolation of total hemispherical emissivity from near-normal emissivity is not well controlled in terms of uncertainty. Such uncertainty could be even less controlled for PRC materials due to their heavily “optically structured” coating.

Based on the identification of the first batch of candidate benchmark materials, measurements of their spectral response across the solar and thermal infrared range are being performed by several partners, reaching wavelengths up to 50 μm . Measurements include spectral and angular data which allow the derivation of the hemispherical emissivity with its corresponding uncertainty. In addition to spectral characterisation, the thermophysical properties of selected samples is also being tested via a combination of the differential scanning calorimetry and the laser flash analysis techniques. These measurements may shed light on the different cooling performance of materials with apparently similar spectral behaviour.

Testing protocols to assess the performance and energy savings deriving from PRC materials

The cooling performance of PRC materials is typically measured using improvised testing rigs under shielding and thermal insulation conditions that are difficult to reproduce and not relevant for real applications, where realistic thermal loads and direct exposure to ambient conditions should be considered. Furthermore, testing of PRC materials should include intense heat conditions and monitoring campaigns spanning months rather than hours/days, which is rarely the case in the literature.

The design of the 4 planned experimental setups for the on-site measurement of the cooling performance of PRC materials is complete, with a fifth prototype planned in addition to the originally proposed ones. An in-depth survey on the sensors employed and the thermal insulation materials required to shield the measurements from external factors has been conducted and will be summarised in a dedicated deliverable document. The size of the small ($< 0.01 \text{ m}^2$), medium (between 0.25 m^2 and 0.5 m^2) and large ($>10 \text{ m}^2$) setups has been defined, as well as their intended application for the cooling of either an air volume, or a water flux. The radiative cooling material selected for the large scale test has been already identified and secured, aiming at a start of the first in-field measurement campaign during the summer of 2024.

Outcomes and impact

The project partners have been engaging in a number of dissemination and communication activities aimed at scientific, metrological and industrial communities, presenting the project objectives and results at 13 national and international conferences. The project has also been presented at COP28 through our collaborator company SPACECOOL Inc. Further communication activities are targeted towards students, by holding seminars on the emerging topic of passive radiative cooling and offering theses on the subject. The dissemination activities led to an expansion of the project's network attracting new stakeholders and potential collaborators. The consortium continues supporting the external Cool White project, and visited a few test sites in Rwanda and performed on-site measurements. All project outputs and related events are promoted on the project website and posted on social media to further engage with stakeholders and the general public.

Outcomes for industrial and other user communities

This project will establish a framework for the performance assessment of passive radiative cooling technologies fostering the development of new energy-saving materials and providing a competitive advantage to EU companies in this emerging field. Companies in the building sector will be able to develop improved materials and coats based on well-defined figures of merit and standardised protocols for their evaluation. Similarly, industries in the HVAC and energy sectors will be able to quantify the energy savings deriving from the synergic combination of active and passive cooling technologies, which is currently not possible due to the lack of reliable models. End users in both communities will further benefit from the guidelines developed within the project for the validation of emissivity measurements with portable instruments and from the identification of a benchmark material exhibiting near unity emissivity for the calibration of such devices.

Outcomes for the metrology and scientific communities

Several critical points of the cooling performance assessment of PRC materials will be addressed within the scope of this project, including the need to account for different atmospheric conditions, geoclimatic regions, and the lack of established figures of merit. By developing validated testing protocols and atmospheric models, the metrological community will be able to address the needs of researchers in the scientific community seeking standardised testing and facilities to benchmark the performances of their proposed materials in an objective and comparable way against well-characterised references. Additionally, highly available PRC materials will be analysed in terms of their spectral and thermophysical quantities, allowing different research groups to compare their laboratory and in-field measurements against well-controlled data.

Outcomes for relevant standards

The output of the project will contribute to the improvement of standardisation in the field of energy performance of building standards providing possible adjustments and amendments to integrate the emerging PRC technologies. Input to Technical Committees engaged in fields such as energy performance of building, thermal insulation, thermal performance and energy efficiency, including CEN/WS 107 on “Mitigation of Urban Heat Island effects with cool materials” is being provided thanks to the direct involvement of consortium members in the relevant TCs. Still to date, in fact, the available documentation on the use of “cool materials” mentions only their ability to “limit temperature increase” rather than exerting a net cooling effect.

Longer-term economic, social and environmental impacts

Technologies optimising the efficiency of cooling will necessarily have long-term economic, social and environmental impacts. Regarding social and health aspects, the emergence of space-cooling as a basic need could exacerbate energy poverty, especially for low-income households, while the inherently passive, all-day, electricity-free nature of sub-ambient radiative cooling offers opportunities for off-grid access to cooling power, thermo-electric generation and daytime solar water harvesting and purification as well as to help curb the heat-island effect in urban environment. On the environmental side, in addition to the benefits deriving from reduced freshwater and electricity consumption, this project also aims at tackling less explored but equally relevant aspects related to the introduction of new materials such as a life-cycle assessment of the different alternatives aimed at evaluating their sustainability and durability to weathering agents, which is especially relevant due to their inherently outdoor application. A preliminary analysis that is currently under consideration, highlighted significant differences between the potential environmental impact associated with the production of a few solutions currently proposed in the literature, which needs to be taken into account when evaluating the benefits deriving from a more widespread adoption of PRC materials.

List of publications

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3. Lorenzo P., Yao L., Lei P., Hongbo X., Xin L., Jérémy W., Zhenmin D. (2023). Patterning of SiO interfaces for radiative cooling applications. *EPJ Web of Conferences*, 287, 04026. <https://doi.org/10.1051/epjconf/202328704026>
4. Ding Z., Li Y., Niu S., Zhao J., Pattelli L., Jaramillo -Fernandez J., Fan X., Li X., Li H., Xu H. (2023). Designer SiO Metasurfaces for Efficient Passive Radiative Cooling. *Advanced Materials Interfaces*, 2300603. <https://doi.org/10.1002/admi.202300603>
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6. Gao H., Pattelli L., Gan W., Wang H., Xiao Z., Wang Y., Li J., Liang D., Xie Y., Li Y., Xu H. (2024). Optical wood with switchable solar transmittance for all-round thermal management. *Composites Part B: Engineering*, 275, 111287. <https://doi.org/10.48550/arXiv.2312.14560>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 Months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRiM, Italy	10. CNR, Italy	18. ALMECO, Italy
2. Aalto, Finland	11. CP, Spain	
3. CMI, Czechia	12. CTI, Italy	
4. CSIC, Spain	13. FIW, Germany	
5. DFM, Denmark	14. NKUA, Greece	
6. LNE, France	15. POLITO, Italy	
7. PTB, Germany	16. ZAE Bayern, Germany	
8. RISE, Sweden	(withdrawn from 31 December 2022)	
9. TUBITAK, Türkiye	17. CAE, Germany (joined from 1 January 2023)	

Publishable Summary for 21GRD04 isoMET

Metrology for European emissions verification on methane isotopes

Overview

Atmospheric observations provide a reality check on the true efficacy of climate change mitigation policy. Methane is a potent greenhouse gas (GHG) with multiple complex sources and stable isotope ratios provide a fingerprint needed to verify emissions by source type. This project seeks to improve 1) ambient air monitoring capabilities; 2) the quality of source signature information; and 3) the modelling information necessary to direct the measurement strategy and make top-down emissions estimates.

Need

Methane is a GHG with anthropogenic and natural sources. Its anthropogenic contribution to climate change is only second in importance after carbon dioxide (CO₂) in terms of its radiative forcing and current emission rates. It also contributes to air quality problems through its role in tropospheric ozone formation. Key source categories for anthropogenic CH₄ emissions in Europe estimated with 'bottom-up' methods suggest a breakdown as: Agricultural sector (~50 %), waste (~22 %), and energy (~15 %). These three sectors account for up to 95 % of global anthropogenic CH₄ emissions and are therefore the focus of mitigation action within the EU through the European Green Deal, and the EU Methane Strategy that describes stronger actions to address CH₄ emissions in each sector. Verifying the efficacy of mitigation policy related to each sector's influence on total CH₄ emissions is not yet possible, yet the measurement and modelling technologies exist. Metrology research is the missing link to bring isotope ratio measurements into operational use for top-down emissions estimation by source category. Integrated Carbon Observation System (ICOS) is the foremost GHG monitoring network for tracking Europe's GHG composition, however, currently formal protocols for measurements and calibration of deployed laser spectrometers do not exist, in turn limiting end-users' confidence to operate such instruments and collaborate as a network of sensors (objective 1). The source signature information needed to interpret atmospheric isotope ratio measurements is lacking. Defined measurement methods that are dependent on the source under study and a centralised system to accrue and disseminate the measurements are needed (objective 2). Further, highly promising new 'clumped' isotope measurements could provide additional observables yet metrology research in Europe in this area is yet to begin. For isotope ratio measurements to have impact on policy and for the measurement strategy to be based on evidence, atmospheric transport modelling activities also need to be stepped up. Understanding the gaps and requirements in measurement for emissions estimation requires a collaboration between metrologists and modellers (objective 3).

Objectives

The overall objective of the project is to develop and deliver an infrastructure for the use of CH₄ isotope ratios in improving emission estimate of CH₄ in Europe.

The specific objectives of the project are:

1. To develop a harmonised in situ CH₄ isotope dataset of ambient air in Europe to resolve compatibility issues of datasets when combining measurements of $\delta^{13}\text{C}(\text{CH}_4)$ and $\delta^2\text{H}(\text{CH}_4)$. This harmonisation includes a) improved methodologies and procedures for comparability of independent in situ analyses of ambient air CH₄ for $\delta^{13}\text{C}(\text{CH}_4)$ and $\delta^2\text{H}(\text{CH}_4)$ by Optical Isotopic Ratio Spectroscopy (OIRS) to the Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW) scales, respectively, and b) Isotope Ratio Mass Spectrometry (IRMS) and OIRS methodologies validated through interlaboratory comparisons across participants.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: May 2024

2. To develop a sustainable metrological infrastructure for a dataset for $\delta^{13}\text{C}(\text{CH}_4)$ and $\delta^2\text{H}(\text{CH}_4)$ -emissions source measurements in Europe and to evaluate the potential for source apportionment through clumped isotopes. This will include developing the analytical protocols for measurements of sources, especially those underrepresented in current databases, and the data analysis and uncertainty estimates for input of new and existing source signature data into inverse modelling for emissions estimation.
3. Use atmospheric chemistry transport modelling to inform objectives 1 and 2, creating estimates of the minimum measurement requirements for deployed instruments. The full dataset of measurements across Europe from objectives 1 and 2 will be used in atmospheric transport models and inverse statistical methods, to enable a first demonstration of estimates of emissions from the new datasets.
4. To facilitate – in cooperation with the EMN for Climate and Ocean Observation and the EMPIR JRP 20NET03 POLMO – the take up of the data and measurement infrastructure developed in the project by key stakeholders such as the global monitoring networks WMO GAW and ICOS and the inclusion in the ICOS and MEMENTO databases.

Progress beyond the state of the art and results

Developing a harmonised in situ CH_4 isotope dataset (objective 1)

Following the success of GHG mixing ratio determination using OIRS, the development of precise real time, in situ field measurements is at hand. The calibration procedures, reference materials and analysis protocols, however, are not sufficiently developed to allow efficient harmonisation of measurements to provide a compatible dataset needed for input in atmospheric transport models. For the first time the consortium will develop such a framework and allow isotope ratio measurements to be used as a complete dataset over a significant spatial and temporal range.

An end-user survey was carried for laboratories outside the project with instruments that measure CH_4 isotopes. From the survey, it was confirmed that there is a lack of reference materials for calibration within the end-user community as well as a lack of a harmonised calibration strategy across the laboratories. Regarding reference materials, the consortium has prepared new static CH_4 reference materials. The reference materials have been distributed to project participants for the calibration and characterisation of their analysers. A metrological concept for harmonisation of CH_4 field site measurements has been developed. The metrological concept will be used by project participants for the harmonisation of CH_4 field site measurements.

Developing metrological infrastructure for a dataset for $\delta^{13}\text{C}(\text{CH}_4)$ and $\delta^2\text{H}(\text{CH}_4)$ -emissions source measurements (objective 2)

For scientific interpretation of ambient air measurements from objective 1, improvements in source signature information are needed. Several studies have looked at sources across Europe, however, the approaches often entail use of different sampling, measurements and data analysis techniques. Improvements are needed in standardisation of measurements, including full uncertainty analyses, and the methods to curate and disseminate results. Attempts have been made at the global level and this project will look to create a more detailed European domain-based database. As with analysis of $\delta^{13}\text{C}(\text{CH}_4)$ and $\delta^2\text{H}(\text{CH}_4)$, OIRS techniques offer another route towards more routine and robust measurements of the rarer isotopologues. This area of research is in its infancy, however, progress in the fundamental metrology behind spectroscopic measurement of these rare ratios will help accelerate advancement and lead to discovery of potentially powerful new observables for source identification.

A new database has been created, supplemented with information required by the atmospheric modelling community as well as clumped CH_4 data. Isotope data from existing databases and literature have been integrated to identify underrepresented emissions sectors, regions, and time periods. Superior spectral regions for selective and sensitive analysis of rare $^{13}\text{CH}_3\text{D}$ and $^{12}\text{CH}_2\text{D}_2$ have been identified by FTIR spectroscopy to improve performance of OIRS analysers. Individual OIRS / HR-IRMS setups for referencing of rare isotopic abundances to stochastic composition have been established, which are the basis for the scheduled comparison of techniques and value assignment of future pure CH_4 reference materials.

Using atmospheric transport models to direct monitoring strategy and improvements (objective 3)

Uniquely the project will use state-of-the-art atmospheric chemistry transport modelling techniques to help understand the measurement requirements and plot the course of future expansion. Atmospheric modelling is

a prerequisite to translating amount fraction and isotope ratio measurements into policy relevant information. Not all measurements are equal in value for use in a modelling framework. Likewise, the uncertainty requirements on measurements can be relaxed in certain instances (where a measurement site is particularly sensitive to emissions) or required to be improved (e.g. for clean air sites that are needed to constrain the amount of CH₄ already present in the atmosphere before additional regional influences). The consortium will use more than one model to quantify where model uncertainty is an important factor to consider in interpretation – the first such detailed study for CH₄ isotope ratios.

Project participants have assessed model output requirements for the project and started comparing model and measurement timeseries. The NAME and FLEXPART models have been run for established sites.

Outcomes and impact

A stakeholder workshop was organised in June 2023 where the project was presented, detailed discussions on how to align the project work with key impact areas were made and feedback was received from the stakeholders. A website (<https://www.npl.co.uk/21grd04-isomet>) has been created for the project to regularly publish output from the project such guidelines and good practice guides. A LinkedIn group (<https://www.linkedin.com/groups/12826690/>) has also been created for the project to publish updates on the project and to get feedback from scientists outside of the consortium. The project was presented at the EURAMET TC-MC SCGA Gas Analysis meeting in February 2024. The consortium presented outcomes from the project at international conferences such as OPTICA 2023 (Germany), Goldschmidt 2022 (France) and NCSLI 2023 (United States). To disseminate expertise learnt in the project, a training session on ¹³CH₃D and ¹²CH₂D₂ measurement using quantum cascade laser absorption spectroscopy (QCLAS) was carried out in July 2023.

Outcomes for industrial and other user communities

This project will lead to confident uptake of the new methods, from using the calibration and measurement protocols to inform how instruments are developed and calibrated by manufacturers, through to the confident use of atmospheric flux estimates by governments and other communities. In development of the protocols for pushing the limits of precision and accuracy of measurement, the project will define the limitation of current instrumentation, therefore finding the most efficient and practical lines for improvement by manufacturers. Calibration standards have been developed in the project. Instrument manufacturers will benefit from the supply of these next generation of accurate calibration standards for isotopic composition, which will enable their instruments to be traceable and provide valid data for atmospheric monitoring. The IPCC has set out the best practises for use of top-down emissions estimates to verify emissions estimates and their reporting to the United Nations Framework Convention on Climate Change (UNFCCC). For these aims governments need to use data established confidently in networks that are linked internationally. The work of this project will inform the practises of such networks based on metrological principles. Other organisations aiming to help governments and industry will be very interested in both the details of this project's work (they themselves make measurements) through to the longer-term outcomes - improved top-down emissions estimates will help direct their mitigation efforts and monitoring strategies (e.g. Environmental Defence Fund (EDF) and International Methane Emissions Observatory (IMEO)).

Outcomes for the metrology and scientific communities

The Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) strategy document (2021-2030) is aligned to the aims of this project including for 2022-2023 'developing an extended global GHG measurement system' and beyond 2023 'interfacing with and providing technical solutions to global stakeholder communities'. The project will extend the remit of ICOS to measurement of isotope ratios of CH₄ and create the solutions required by the stakeholder community through its focus on using atmospheric transport modelling. The consortium will therefore be able to realise the aims of the CCQM strategy within the timeframe of this project and include the contribution to standards. Through this effort other scientific groups will have the confidence to operate more instruments, thus bringing more measurements to a combined dataset, ultimately improving the quantity of high quality in situ observations which are critical for scientific research and for eventual routine top-down assessment of CH₄ emissions. There is also a wider isotope ratio measurement community looking to use OIRS techniques for measurement of GHGs and other species. Stable isotope ratios and radioactive isotope ratios across other GHGs (name CO₂ and N₂O) also hold significant value for understanding the carbon and nitrogen cycles and the sources of emissions. Many of the techniques and approaches that will be developed for CH₄ isotopes could be adapted across other measurement systems.

Outcomes for relevant standards

In terms of standardisation, the project activities are broad, ranging from the preparation of gas standards to the methods of emissions estimation. The ISO technical committees targeted will be ISO/TC 158 (Analysis of gases), ISO/TC 146 (Air quality) and ISO/TC 207 (Environmental management). The project participants that have connections via their institute or direct memberships of these committees will ensure that the knowledge developed within the project is fed into the committee meetings. The project is having a strong impact in the CCQM-GAWG-IRWG-TG-ISOTOP task group where participating consortium members provide input on the experiences learned within the isoMET project. Also, the project will have a strong impact in stakeholder-led standardisation activities (e.g. the reports from outputs of the WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques (GGMT) or the ICOS Monitoring Station Assembly (MSA) Atmosphere Meeting).

Longer-term economic, social and environmental impacts

Economic

An increasingly rapid policy response will be vital to enhance responsiveness on the move towards net zero in under 30 years while ensuring any possible negative economic costs are minimised. The EU 2030 Climate Target Plan Impact Assessment suggests an accelerated effort to tackle CH₄ emissions: A requirement of 35 % to 37 % CH₄ emission reductions by 2030 compared to 2005 – a significant step up for effectiveness of policy action. With binding emission targets being set accounting for emission changes is now inherently linked with decision making by local, regional, and country level governments regarding the wider economy. Issues of trade-offs e.g. in policies that might limit CH₄ emissions but increase CO₂ emissions and perverse incentives (for example in the biogas industry) are further detailed economy-related reasons to improve the transparency behind emissions reported, including top-down verification. The EU aims to spend 30 % of its overall budget for 2021-2027 on tackling climate change and its effects (www.consilium.europa.eu/en/infographics/recovery-plan-mff-2021-2027/). Targeting the right mitigation measures for investment will enhance the effectiveness from this budget and prevent unnecessary spending on mitigation measures that are ineffective. If emissions can be broken down by sector/industry it will lead to greater engagement with the relevant industries responsible for those emissions, making way for direct economic impact through improvements in GHG mitigation efficiency at the industry level. Air pollution can also considerably benefit from mitigation of CH₄ emissions (being a major cause of ground-level ozone pollution), affecting health, including both mortality and morbidity, and agricultural productivity. This has knock-on effects for the economy and the welfare costs from premature deaths and pain and suffering are quantitatively assessed.

Environmental

Methane makes up a significant part of the anthropogenic radiative forcing that is driving the global rise in temperature (now around ~1 °C above preindustrial). The IPCC have reported that limiting a temperature rise this century to 1.5 °C could avoid the most harmful effects of climate change, which include huge changes to the environment and loss of biodiversity in terrestrial ecosystems (Masson-Delmotte et al., 2018); above this threshold the chances of loss of unique and already threatened ecosystems become very likely. Other areas of the planet are already under significant strain from rising temperatures due to the rising total of global anthropogenic GHG emissions. Methane is an especially strong greenhouse gas with the effective radiative forcing in 2019 from 1750 at 0.54 W m⁻², second only to CO₂ at 2.16 W m⁻² (IPCC, 2021). The global warming potential for every mass unit of emissions of CH₄ is 27-30 times greater relative to CO₂, making significant emission reduction of CH₄ vital for reaching climate targets. Europe therefore has a role to play in limiting these global environmental problems by leading the way in climate mitigation action. Objective measurement and understanding of these issues can help to make the right balance of decisions to protect the environment.

Social

Methane emissions mitigation policy will impact how we grow food through to how we heat our homes. Outcomes from projects like this to understand the primary sources of methane emissions will ultimately accelerate changes that need to be made in one sector over another. Climate change mitigation policy is also an opportunity to address societal equity, ensuring that emissions mitigation measures do not burden the most vulnerable through unfair policies. Direct GHG emissions mitigation measures will complement other developments for policies aimed at the agriculture sector and rural areas, in particular an expected societal shift to more balanced diets, with less red and processed meat, more fruits, vegetables and plant-based protein sources, in line with the EU Farm to Fork Strategy.

Future uses

Developing the protocols and methods for this new measurement network will allow CH₄ isotope ratios to be an integral part of established country-scale operational emissions verification systems that are now considered 'best practice' for reporting to the UNFCCC. The project provides a scientific platform to expansion of isotope ratio networks to higher resolution spatial coverage or different areas of the planet.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
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Project website address https://www.npl.co.uk/21grd04-isomet		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	4. StockholmU, Sweden	
2. TUBITAK, Türkiye	5. UHEI, Germany	
3. VTT, Finland	6. UU, Netherlands	
	7. UVSQ, France	
Associated Partners:		
8. Empa, Switzerland		
9. NPL, United Kingdom		
10. RHUL, United Kingdom		
11. UoB, United Kingdom		
12. UofG, United Kingdom		



Publishable Summary for 21GRD05 Met4H2 Metrology for the hydrogen supply chain

Overview

The urgent need to mitigate climate change and to limit greenhouse gas emissions is driving actions to reduce the use of fossil fuels. However, meeting current and future energy needs necessitates the increased use of alternative energy sources such as hydrogen from renewable sources. To achieve this goal, the metrological infrastructure for hydrogen needs to address all parts of the supply chains. This project will provide novel and improved standards for the safe application of hydrogen flow measurement, hydrogen quality assessment and custody transfer. Together with outcomes from previous projects, an infrastructure will be established that provides measurement data that are fit for demonstrating compliance with regulations and contracts. This infrastructure will facilitate ramping up the use of hydrogen and society to adapt to using hydrogen instead of fossil fuels.

Need

The report from the Intergovernmental Panel for Climate Change of 2021 underlined once more the urgent need to reduce greenhouse gas emissions to mitigate climate change. The European Commission developed the European Green Deal to decarbonise energy use, shifting from fossil fuels to renewable fuels. One of the pillars is a phased approach to the introduction of hydrogen to replace fossil fuels in electrical power generation, transport, industry and the built environment. In addition, recent geopolitical developments on the edges of Europe have further highlighted the need for diverse, reliable and resilient, non-fossil fuel-based energy supplies in Europe. To apply hydrogen safely within the existing gas grid network and other infrastructure, traceable measurements for leak testing, material compatibility, sensors for monitoring processes and odorization are required to demonstrate compliance with legislation. Traceable flow measurement and hydrogen quality assessment are necessary for custody transfer and fair trade. Demonstrating compliance with hydrogen quality specifications, such as ISO 14687, and legal metrology requirements, such as International Organization of Legal Metrology (OIML) R140 and OIML R137, for metrological type approval and for assessing the performance of measuring systems, is therefore essential. Hydrogen sampling methods for applications below 20 MPa, such as gas grids, need to be developed and validated, to ensure metrological traceability and reliability of data obtained using those methods.

Metrological traceability and accuracy already developed need to be deployed to onsite measurement systems, so that robust and comparable results are obtained that support their use beyond monitoring processes. Finally, there is a need to improve and expand documentary standards for totalisation of quantity and energy used for custody transfer, such as OIML R140, ISO 15112 and EN 1776, to make them fit for purpose for use with hydrogen-enriched natural gas and hydrogen and to cover the totalisation of impurity content.

Objectives

The overall objective of the project is to further develop and integrate the metrology necessary to support the entire supply chain of hydrogen, from production to storage and end use. The project will disseminate metrological traceability to the field, so that measurement results become fit-for-purpose with respect to health, safety, environmental, and fiscal purposes.

The specific objectives of the project are:

1. To develop calibration and measurement methods to support reliable, traceable, and accurate measurements of hydrogen in production processes and end-user applications, in view of safety, process efficiency and environmental issues, such as for purity, leak detection, odorization, and

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued June 2024

materials performance, ensuring that online measurement instruments and sensors are operating within their specifications (e.g., to ISO 14687, OIML R139, and OIML R140).

2. To develop measurement standards to enable calibration and validation of flow metering equipment under actual conditions (pressure, temperature), used to accurately quantify flow rates of hydrogen (including blended hydrogen) through the hydrogen supply chain, and to facilitate compliance with respect to, e.g., OIML R137, OIML R140, and the Measurement Instruments Directive.
3. To develop and improve measurement standards and methods to enable traceable validation and performance evaluation of gas quality measurement methods for hydrogen, to thus improve on the current lack of equivalence for impurities, e.g., oxygen, hydrogen sulphide, moisture content, and for reactive components such as hydrogen chloride and chlorine. To develop and improve analysers for critical impurities for online monitoring of changes in gas quality, through the supply chain and processing equipment, to ensure the gas quality meets the required specifications (ISO 14687).
4. To develop novel methods for the evaluation of measurement uncertainty along the supply chain as a whole, namely with regard to the measurement of total quantity, and energy and impurity content of hydrogen and hydrogen blends.
5. To facilitate, in cooperation with the European Metrology Network Energy Gases, the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers for hydrogen), standards developing organisations (ISO, OIML) and end users (e.g., industry, consumers, power generation and transport).

Progress beyond the state of the art and results

To develop calibration and measurement methods to support reliable, traceable, and accurate measurements of hydrogen in production processes and end-user applications, in view of safety, process efficiency and environmental issues, such as for purity, leak detection, odorization, and materials performance, ensuring that online measurement instruments and sensors are operating within their specifications (e.g., to ISO 14687, OIML R139, and OIML R140).

Calibration standards for measuring hydrogen leaks have been designed and are being constructed. Different measurement principles are used, such as the pressure-temperature-volume behaviour of the fluid, refractometry and gravimetric flow measurement. The first version of the transfer standard was designed and used in the preliminary metrological validation of one of the designed calibration standards.

A high-pressure permeation setup was designed considering the recommendations and specifications of ISO 15105-1. This standard describes a general method for measuring the gas-transmission rate in plastics. A permeation cell was designed for the setup, as well as the two sample holders for O-rings and sheets/foils. Permeation measurements at pressure differences up to 300 bar on high performance polymer foils and hydrogen certified O-rings were successfully performed.

A comprehensive protocol for the evaluation of the performance of sensors used in hydrogen production, upgrading, transportation and use is being developed. The following metrological metrics (e.g., accuracy, baseline, cross-sensitivity (selectivity), drift, environmental effects, final indication, hysteresis, limit of quantification, linear range/measuring range, noise, operational range, uncertainty, response/recovery time, reversibility, resolution, saturation, sensitivity) are being taken into account.

Based on the literature review of odorization of natural gas and hydrogen, reference gas mixtures were specified and will be prepared in duplicate. Analytical methods for various sulphur compounds at ppm-level have been optimised. Experiments were performed to assess the matrix effect of hydrogen, hydrogen-enriched natural gas and methane as matrix. A sulphur-free odorant was selected to prepare gravimetric reference gas mixtures at the ppm level in hydrogen in cylinders with potentially suitable passivation treatment. One gas mixture for each odorant is being prepared. Based on stakeholder input, two mixtures with 2-hexyn in hydrogen are being prepared and will follow the stability by using an internal standard (benzene) in the mixture.

To develop measurement standards to enable calibration and validation of flow metering equipment under actual conditions (pressure, temperature), used to accurately quantify flow rates of hydrogen (including blended hydrogen) through the hydrogen supply chain, and to facilitate compliance with respect to, e.g., OIML R137, OIML R140, and the Measurement Instruments Directive.

A literature study related to the use of hydrogen in pipelines in Europe has been prepared. It details the gas distribution grids and specific plans to use the grid to transport hydrogen.

An evaluation of existing gas models for gas flow suitable for hydrogen was produced and accepted by the consortium. It assesses whether models for air or natural gas can correctly model hydrogen flow for different applications and flow conditions.

A document investigating the development of supply chain containing liquid hydrogen is in preparation.

The preparation of a travelling standard for the comparison of primary flow measurement standards for hydrogen-enriched natural gas, and the construction and characterisation of the transfer package have started. A protocol is being developed detailing the comparison process and calendar.

For the development of a primary flow standard for domestic gas flow meters, a reference flow meter was chosen. The development of the facilities was started by designing these and procuring the parts necessary to the construction. The facilities are at different stages of advancement depending on the partners, from under procurement to being operational.

Finally, with input from the Stakeholder Committee a survey was created and distributed among the networks of the participants to enquire the need for calibration facilities for large-capacity flow meters for hydrogen flow in Europe. The purpose is to create a roadmap for such a pan-European infrastructure, so that the gas industry has access to metrological traceability for hydrogen flow meters for gas grids.

To develop and improve measurement standards and methods to enable traceable validation and performance evaluation of gas quality measurement methods for hydrogen, to thus improve on the current lack of equivalence for impurities, e.g., oxygen, hydrogen sulphide, moisture content, and for reactive components such as hydrogen chloride and chlorine. To develop and improve analysers for critical impurities for online monitoring of changes in gas quality, through the supply chain and processing equipment, to ensure the gas quality meets the required specifications (ISO 14687).

Requirements were drafted for sampling points which are considered representative of pressure, temperature, humidity, sampling frequency, safety, and volume. Existing hydrogen sampling standards, guidelines and current practices were reviewed, including ISO/AWI 19880-9. Based on these outcomes, a sampling rack was designed and built. The sampling system was also specified for pressures up to 70 MPa, which is equipped with a safe venting of hydrogen. A second rig is being constructed, suitable for operation at 1-to-10 bar.

A transportable precision humidity generator (TPHG) was designed, developed, and commissioned to provide state-of-the-art on-site traceability to trace water measurements in hydrogen. The TPHG, first of its kind, is cooled with ethanol and operates between 0.2 MPa and 5.5 MPa, with water amount fractions from 0.5 ppm to 50 ppm or, equivalently, between -55 °C and -10 °C pressure dew point. Various instruments, based on different technologies, are available for validating the new TPHG in an ATEX-grade laboratory. Trials were started to prepare a primary gas reference material of water vapour in 3 types of hydrogen gas cylinders. Currently the fillings are up to 3 MPa at 5 ppm water in nitrogen. The short-term stability is good, and the agreement is within ± 0.1 ppm when compared to dynamically prepared gas mixtures. Additionally, an existing high-pressure dewpoint generator (HPDG) is being adapted for trace water measurements in hydrogen. The HPDG is designed to operate between 0.1 MPa and 6 MPa, with water amount fractions from 0.5 ppm to 100 ppm. The adaptation of the HPDG is nearing completion and the performance of the HPDG with H₂ carrier gas will be characterised with a cavity ring-down spectrometer.

The feasibility of preparing mixtures of chlorine in nitrogen was assessed, starting from a commercial mixture of chlorine in nitrogen. Analyses were performed with cavity-enhanced absorption spectroscopy. Using mass-flow controllers to create calibration gas mixtures at different amount fractions, a calibration curve was recorded.

Not much literature is available on the stability of hydrogen chloride in hydrogen. The preparations have started on a stability study of these calibration gas mixtures and a new HCl analyser has been purchased. The upgrading of the portable reference gas generator (based on the evaporation method) for hydrogen chloride in a hydrogen matrix at amount fraction 10 nmol/mol to 10 μ mol/mol with relative uncertainties between 3 % to 5 % has started. The generator will prepare calibration gas mixture with about 0.1 % (volume fraction) water.

The development of a multicomponent gas analyser based on the far-UV spectroscopy, suitable for on-line/off-line simultaneous measurements of multiple compounds i.e. impurities (e.g., hydrogen sulphide, water and carbon dioxide) in hydrogen has started. The analyser is equipped with temperature sensors and a pressure sensor for pressures up to 5 MPa and suitable for measurements up to 4 MPa in H₂. In the design of the analyser experience and results gained in high-pressure permeation work have been accounted. First

measurements with ultra-pure gases (6.0 grade) such as Ar, N₂ and H₂ up to 50 bar have been done. The measurements show that simultaneous measurements of e.g. H₂S, CO₂, H₂O, O₂, CO, HCl and Cl₂ under given amount fractions should be possible to perform in on-line continuous analyser operation. The analyser will next be validated using a transportable dynamic vapor generator developed in the project.

The first mixtures necessary for improving the total sulphur analysis in hydrogen were prepared, starting at the low ppm-level hydrogen sulphide. A two-step dynamic dilution setup was designed. Parts, including the mass flow controllers were ordered.

Work has started on the development of a traceable laser spectroscopic method for ammonia in the range 50 nmol/mol to 500 nmol/mol. The setup is ready for the first tests.

A compact versatile photoacoustic on-line analyser was developed. The analyser uses NIR and/or MIR spectroscopy capable of monitoring the most important impurities. Currently the design is being further developed and detailed. The analyser is under construction.

To develop novel methods for the evaluation of measurement uncertainty along the supply chain as a whole, namely with regard to the measurement of total quantity, and energy and impurity content of hydrogen and hydrogen blends.

A general framework for the calculation of uncertainties in the total volume, energy and purity exposure based on models described in, e.g., OIML R140, EN 1776 and ISO 15112 was set up. The framework includes the AGA8 and GERG-2008 equations of state. Uncertainty evaluation uses both the law of propagation of uncertainty and the Monte Carlo method. The input of data to the computational framework is standardized, using a modular approach that is adaptable to metering station configuration and other calculation methods.

Using the computational framework, an outline of software for calculating the uncertainties in the measurands of interest (total quantity, energy and purity exposure) was set up and implemented. The framework provides the quantities relevant to volumetric quantity and energy measurement. In a later stage, simpler cases such as measuring quantity on a mass basis will be implemented.

Existing uncertainty models were assessed and analyzed to address the correlation among measurements taken with the same instrument. Data from natural gas metering stations was used to make the assessments. Models were developed for assessing correlations between flow rate, temperature, pressure and composition measurements. Work has started on the analysis of the time variation of parameters of interest such as quantity, energy content, and impurity, due to the presence of, e.g., daily or seasonal cycles. The present serial correlation under more or less steady-state conditions inflates uncertainty by some 30 %, assessed on two datasets. Different computational techniques for the totalization of relevant parameters were assessed. A distinction between deterministic and random signals was made by applying time-domain filtering method. The discretization error of the totalization was estimated and found to be proportional to N^{-2} .

Outcomes and impact

The project was presented at several conferences and international meetings. A website was created, and a LinkedIn page created. Two meetings with the Stakeholder Committee (SAB) took place, providing guidance on the implementation of the project. The first meeting with the SAB took place on M3, the second on M12, following a Stakeholder Workshop open to the public. The work on odorants attracted the interest of ISO/TC193/WG5 and MARCOGAZ. The work on the evaluation of measurement uncertainty attracted the interest of ISO/TC193/WG7 and JCGM WG1 (GUM). Several other standardisation committees were contacted and the information about the project activities was shared. The project team organised a bilateral meeting with the EMN Energy Gases at the beginning of the project to agree processes for information sharing; since then, communication actions were coordinated. The progress of the project is regularly presented to the EMN Mathmet as well.

Outcomes for industrial and other user communities

This project will support the industry involved in the hydrogen supply chain from hydrogen production to transport and end use.

Novel measurement standards for hydrogen leak rate measurement will enable industry to have reliable devices to monitor the integrity of gas grids, thereby ensuring safety when feeding hydrogen into these grids. The methods and standards for material compatibility assessment will enable universities, research institutes and industry to assess materials for their suitability to be used with hydrogen, ensuring that potential hazardous

situations are recognised at an early stage. The odorization standards will enable gas grid operators, for example, to confirm that the odorant level in hydrogen enriched natural gas (HENG) and hydrogen meets the specifications, thereby ensuring the safe distribution of these gases to the built environment. They also enable research institutes and other bodies to assess the olfactometric properties of these odorants with hydrogen-containing energy gases.

The rigs developed for the calibration and evaluation of sensors for hydrogen quality will enable users and producers of these sensors to have them assessed, so that these sensors have a known performance, and the results obtained are metrologically traceable. This traceability in turn enables users of the sensors to apply them beyond the monitoring of processes, thereby avoiding the need to measure again for, e.g., assessment of compliance with specifications.

The validated primary standards for flow metering of hydrogen-containing energy gases will enable custody transfer for these gases, in combination with the methods for sampling and hydrogen quality assessment, and the improved methods for totalisation and the associated measurement uncertainty evaluation.

The hydrogen quality measurements performed at two industrial sites, electrolyser plant and gas pipeline, will demonstrate to the industry how metrological traceability and accuracy can be delivered in real-life situations. These demonstrations and the good practice guidelines derived from them, will create a close link with the hydrogen production and transport sector as well as with the measurement system manufacturers and therefore, ensure a swift take up of project outcome.

Outcomes for the metrology and scientific communities

To facilitate the take up of hydrogen in Europe and worldwide, a well-established measurement infrastructure is a must. This project focuses on developing, optimising and comparing traceable measurement standards and methods, so that this infrastructure is created.

The novel flow measurement standards will enable NMIs, DIs and calibration laboratories to provide measurement services for the hydrogen supply chain and industry to have their instruments calibrated. These in turn enable research into the development of gas meters for HENG and hydrogen. The sampling methods, standards and methods for hydrogen quality assessment will enable services to be provided by the gas industry in the form of secondary and working gas standards and measurements and will provide research groups with the necessary tools to ensure their measurement results are metrologically traceable, so that conclusions from their work can directly be taken up by others.

The improved methods for hydrogen quality assessment will enable metrological traceability to be disseminated to laboratories, which in turn can seek accreditation based on ISO/IEC 17025 for their services related to ISO 14687, including sampling. Research groups will benefit from these capabilities in that they can assess improvements in processes along the supply chain with the necessary standards for calibration of their equipment.

Legal metrology organisations and their national bodies benefit from the work related to especially OIML R137 and OIML R140, as well as the calibration and measurement services enabling assessment of the performance of measurement equipment supporting conformity assessment and type approval. The first contacts have been made and efforts are now targeted at providing input to the ongoing revision of OIML R140.

Outcomes for relevant standards

The project will provide enhanced guidance for calculating the total quantity, energy and impurity exposure of supplied or received gas and good practices in taking into account the dynamics of the gas grid and gas properties in the uncertainty evaluation to OIML R140 and ISO 15112. The work on flow measurements will provide evidence as to whether OIML R140 can also be applied to metering and custody transfer of hydrogen and HENG. Material compatibility testing is covered in standards such as ISO 15105 and ISO 2782; the first possible contributions of approaches for increasing the sensitivity of the measurement and set-up adjustments have been presented. The results in WP3 will demonstrate that the scope of ISO 21087 can be extended to supply chains other than just PEM fuel cells. The materials compatibility overview for calibration gas mixtures in ISO 16664 can be updated based on the stability study data for static gas standards with, e.g., hydrogen chloride and moisture.

Longer-term economic, social and environmental impacts

As natural gas is the primary fuel source for heating in Europe, the market is approximately 550 billion cubic metres per year. The introduction of hydrogen in this part of the gas supply relieves the pressure on the electrical grids. This project will provide the tools to adapt the measurement infrastructure to distributing HENG

in the first instance, and hydrogen at a later stage. Using HENG comes with relatively small changes for end users, and thus is a very economical measure to decarbonise the gas supply in the short term. It is also far less disruptive than requesting end-users to switch from gas to electricity for these purposes.

The outcomes support the safe application of hydrogen in gas transmission and distribution systems, as well as charging end-users and industry for their gas use in accordance with current requirements. Thereby it facilitates the transition from fossil fuels to net-zero carbon dioxide emission renewable fuels. Feeding in hydrogen enables end-users and industry to gradually adapt to this future, with as little disruption as necessary. In the coming years, feeding in green hydrogen in the natural gas grids leads to a reduction of carbon dioxide emissions, thereby contributing to meeting intermittent goals of the European energy system.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 October 2022, 36 months
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Project website address: https://met4h2.eu/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. VSL, Netherlands	16. DTU, Denmark	25. SICK, Germany
2. BAM, Germany	17. ENVIPARK, Italy	
3. BEV-PTP, Austria	18. GERG, Belgium	
4. CEM, Spain	19. Nippon Gases, Italy	
5. Cesame, France	20. NORCE, Norway	
6. CMI, Czechia	21. POLITO, Italy	
7. CNAM, France	22. UL, Slovenia	
8. DFM, Denmark	23. ZAE Bayern, Germany - ceased participation on 31 December 2022	
9. FORCE, Denmark	24. CAE, Germany - joined the consortium on 1 January 2023	
10. INRIM, Italy		
11. JV, Norway		
12. LNE, France		
13. PTB, Germany		
14. RISE, Sweden		
15. VTT, Finland		
Associated Partners:		
26. METAS, Switzerland,		
27. NEL, United Kingdom,		
28. NPL, United Kingdom		



Publishable Summary for 21GRD06 MetCCUS Metrology Support for Carbon Capture Utilisation and Storage

Overview

Europe must make reductions in CO₂ emissions in order to meet stringent reduction targets related to global warming. Carbon capture utilisation and storage (CCUS) can be used to remove the CO₂ produced by industrial processes for storage either underground or locked in an alternative material. It is versatile, in the sense that the CO₂ removal step can complement any process e.g. production of power, fuels, chemicals and heating. In order to facilitate efficient and safe usage of this technology across Europe and to support the CCUS industry, this project will address key measurement challenges related to flow metering, emissions monitoring, chemical metrology and the physical properties of CO₂.

Need

The European Union set a target to reduce greenhouse gas emissions by 55 % by 2030 and to become carbon neutral by 2050. To support meeting these ambitious targets the Green Deal was introduced which specifically states that “priority areas include clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilisation”. As of the end of 2020, several European countries including Czechia, Finland, France, Germany, Portugal, the Netherlands, Denmark and the UK had included CCUS as part of their national strategies. The European Commission has acknowledged the role that CCUS plays in meeting this target, but have also stated that “the environmental integrity of CCUS is their overriding concern”. Monitoring of carbon dioxide through flow metering within the delivery system and through leak monitoring outside the system is key to quantifying real amounts of carbon dioxide captured (Objective 1). Directive 2009/31/EC on the geological storage of carbon dioxide stated a requirement of a regulatory framework for monitoring CO₂ leakage which was established through the Emissions Trading System (Objective 2). Additionally, as highlighted by the European Metrology Network for Energy Gases in their annual Strategic Research Agenda and in an energy transition report on CCUS measurement challenges authored by NPL with contributions from NEL, new requirements for measurement solutions were identified for CO₂ quality assurance, physical properties and material testing, such as pipeline corrosion and capture solvent degradation (Objectives 3 and 4). The reports were written following direct consultation with over 300 stakeholders from European industry including the key players within the CCUS field. This will be the first metrology for CCUS project that will solve the key metrology challenges for CCUS identified by industry and it will provide the Primary Standards, methods, good practice guides and literature reviews that they require to successfully grow a CCUS industry in Europe.

Objectives

The overall aim of the project is to develop new metrology tools in the form of Primary Standards and methods, as well as the relevant best practice/guidance, necessary to support industry in carbon capture utilisation and storage. The specific objectives of the project are:

1. To develop a metrology infrastructure for monitoring the CO₂ gas-flow and CO₂ liquid-flow as required by the CCUS industry with target uncertainties of 1.5 % – 2.5 %, including development of primary facilities and transfer standards, by investigating existing flow facilities for the possible use with CO₂ and development and intercomparison of new facilities for both intermediate scale (typically below 50 m³/h and low pressure) and large scale flow ($Q_{\max}$ = up to 400 m³/h and higher pressure).

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: June 2024

2. To develop the metrological support to enable the measurement and reporting of emissions to air from different stages of the CCUS process; including novel methods to determine emissions to the atmosphere through carbon capture processes, infrastructure (leaks), or geological storage.
3. To develop new standards and measurement methods to support European industries with performing the gas composition measurements required for carbon dioxide within CCUS; including primary reference materials with low-level impurities in CO₂, sampling methods to determine the material compatibility of key impurities in CO₂, online gas analysers for monitoring impurities in CO₂ as well as to determine CO₂ quality.
4. To establish the metrological infrastructure to support the design, monitoring and maintenance of industrial infrastructures dedicated to carbon capture, transportation, utilisation, and storage; including development of a coherent empirical model for understanding the thermophysical properties of CO₂, and sensors and procedures to preserve the efficiency of the transportation and utilisation of CO₂.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (ISO TC 265) and end users (CCUS industry).

Progress beyond the state of the art and results

The progress beyond the state of the art for the objectives and the planned results from this project are:

Metrology infrastructure for monitoring the CO₂ gas-flow and CO₂ liquid-flow (objective 1)

No independent, traceable, flow calibration facilities are available for calibrating flow meters with carbon dioxide across the full range of conditions which are likely to occur in capture, transport and storage. Carbon Capture and Storage (CCS) streams may be in gas, liquid, dense phase, or possibly supercritical state at metering locations. Investigation is required into the risk of operating near phase boundaries where phase change and two-phase flow could affect accuracy and the effects of impurities could shift the phase boundaries. New traceable flow calibration facilities and primary standards will be developed in this project to evaluate the performance of various flow meter types when used with gaseous and liquified carbon dioxide including an assessment of the lowest uncertainties. The project will also provide guidance on calibrating these meters with alternative fluids that are common in laboratories.

Primary volumetric facilities have been upgraded at the start of the project for intermediate scale (up to 30 m³/h and atmospheric pressure) and large scale (up to 400 m³/h and P_{max} = 65 bar). In the next phase of the project measurements will start to calibrate flowmeter with pure CO₂ gas, including intercomparisons between project participants, and to determine the transferability with alternative gases. A strategy to provide a traceability chain for large scale calibration facilities starting from the intermediate primary standards will be developed. Literature research was performed and the first report will be published in May 2024 "Summary on the Current State of the Art in Traceable Liquid CO₂ Flow Measurement". Furthermore, CO₂ fiscal metering requirements applicable for CCS fiscal metering at an international and European level were determined.

Metrological support for measuring and reporting of CO₂ emissions to air (objective 2)

Methods for accurately measuring emissions from post-capture flue gas (including amines present in capture solvents) have not been developed and validated, yet. The project will develop a facility capable of simulating emissions from post-capture flue gas and new methods to monitor emissions (Proton Transfer Reaction Mass Spectrometry (PTR-MS), Cavity Ringdown Spectrometer (CRDS), Fourier-Transform Infrared (FTIR)).

Potential techniques for monitoring and quantifying carbon dioxide leaks from pipelines and storage sites (including sub-sea) are available (e.g. acoustic imaging, sonar bathymetry and tuneable diode lasers) but these techniques have not been validated as possible methods for quantifying leaks for sites. To ensure the performance of these instruments meets industry requirements, testing must include accuracy, selectivity (against air and other leaks), spatial resolution and repeatability. The project will develop capability to simulate precise CO₂ leaks from pipelines to test and validate commercial new leak monitors. Further, methods will be developed to monitor large scale CO₂ leaks from on-shore and sub-sea storage sites using state of the art gas detection techniques such as LIDAR and other spectroscopic methods.

Input has been collected for several reports: 1) requirements for post combustion carbon capture (PCC) emissions monitoring, 2) methods for nitrosamine monitoring and 3) identification of CO₂ leak scenarios from storage such as sub-sea leaks. The controlled release system has been modified to generate CO₂ test

emissions and trialled the use of the system. Work is underway to develop test procedures for the system to perform traceable calibration of equipment for CO₂ emission monitoring.

Chemical metrology (objective 3)

For accurate composition measurements, offline analysis will be needed. Some reference mixtures have been prepared previously by research organisations (such as SINTEF); however, these have been mainly high amount fraction inert gases in carbon dioxide to support fluid property measurements. The project will identify the key impurities in CO₂ that need to be measured by industry, and it will develop the analytical methods, Primary Reference Materials and good practice for sampling.

The solvents used in capture materials degrade over time; there is a need for a measurement method that can monitor solvent degradation and for the validation of the analytical techniques that can monitor for the release of additional impurities due to the breakdown. The project will develop a testing rig capable of subjecting capture solvents to high temperatures under controlled CO₂ atmospheres (containing varying levels of impurities). This facility will allow CO₂ capture cycling to monitor degradation and the presence of impurities from the material.

An overview with all the impurities and corresponding amount fractions present in CO₂ in the CCUS industry has been performed that has determined for which impurities the primary reference materials were prepared. Currently a stability study of the reference materials is conducted and dynamic methods for preparation of primary reference materials for the CCUS industry are under development. Two reports have been written: 1) "Literature survey on commercially available cylinders for the preparation of PRMs for CCUS" and 2) "Literature survey on current state-of-the-art for the material compatibility of vessels for the sampling of CO₂ for CCUS". Both reports are available on the project website.

Understanding the physical properties of CO₂ to support CCUS industrial infrastructure (objective 4)

Knowledge of the thermophysical properties of carbon dioxide mixtures with a range of potential impurities, and within the operational conditions of CCS processes, presents some gaps between the experimental data and the requirements of the system design and operation. Even complex equations of state (Lee-Kesler, SAFT and GERG) do not provide accurate results for the pressure, volume and temperature (PVT) properties and the vapour-liquid equilibrium (VLE) for carbon dioxide mixtures. The development of a specific reference equation of state and mixing rules for CCS is essential and underway (e.g. Equations of State for Combustion Gases (EOS-CG)), for which the density, speed of sound and VLE data of the selected mixtures is needed. Although EMPIR JRP 20IND10 Decarb included a literature review of this data, no laboratory work was performed. One work package in this project will be dedicated to physical property measurements, which includes experimental work to provide traceability for a physical property (density, viscosity, heat capacities and speed of sound) at a specific gas composition (made traceable through the preparation of binary mixtures). Furthermore, activities will be focused on developing new equations of state models and uncertainty budgets.

Three different compositions for binary mixtures of CO₂ with amines have been selected and a measurement protocol has been tested. The measurements have been performed, measuring the density at (313 and 393) K at ambient pressure only for Methyl Ethyl Amine (MEA) at 30 % with 0.2 mol CO₂/mol MEA, measuring density of MEA at 30 % with 0.2 mol CO₂/mol MEA, for temperatures between (293 and 393) K and pressures up to 10 MPa, and speed of sound measurements starting with MEA at 30 % with 0.2 mol CO₂/mol MEA, for temperatures between (303 and 393) K and pressures up to 12 MPa. Existing equations of state have been evaluated and the most relevant equations of state models for CCUS processes and flow metering are the EoG-CG 2019 and GERG 2008. Finally, initial trials were performed with instrumentation for the calibration of humidity in CO₂ and a new test facility to perform corrosion rate measurements in dense phase CO₂ has been developed.

Outcomes and impact

During the first half of the project, to maximise the impact of the project and ensure a wide dissemination of the knowledge generated, the consortium gave 26 presentations at conferences and workshops. A website (www.metccus.eu) and LinkedIn page ([MetCCUS: Overview | LinkedIn](#)) were created. Furthermore, a 29-member stakeholder committee was set up containing members from industry end users, regulation policy makers, standardisation bodies, instrument manufactures and academic institutes. In December 2022 the first stakeholder advisory board meeting took place with around 13 stakeholders from various European countries. This was followed by a second meeting in August 2023 with around 15 stakeholders from various European countries. The first MetCCUS seminar took place in October 2023. Over 120 people attended. A total of 12

speakers gave presentations, some of them from the consortium and some external stakeholders that accepted the invitation. There was a very good use of the network of the advisory board and other connections. The seminar enabled a good interaction with stakeholders, several inputs were received during the meeting and after (circulated survey), to understand their needs and feed them into MetCCUS. The recording of the seminar and the material presented can be found on the project website.

Outcomes for industrial and other user communities

Using the CO₂ primary standards, the leak monitoring methods and the reports/guides developed in this project, CCS operators will be able to perform flow metering and leak monitoring of CO₂ to accurately quantify amount of CO₂ capture, transported, stored and lost in their process. This is required to operate the facilities safely, but also to quantify CO₂ capture and losses when reporting.

Using the Primary Reference Materials, new gas analysis methods, a materials testing facility, physical property methods and other guidance developed in this project, CCS operators and CO₂ suppliers will be able to determine suitable conditions and materials (e.g. pipelines). In addition, they will be able to monitor these conditions through purity and physical property measurements to ensure safe and efficient operation. Knowledge will be transferred from the project to users by sharing all reports and good practice guides on the project website as well as to stakeholders by sharing these documents and any other developments (methods and standards) through a LinkedIn profile page. Four reports have been published up till now: 1) current state of the art of traceable liquid CO₂ flow measurement and liquid CO₂ primary standard requirements (<https://zenodo.org/records/11118645>), 2) literature survey on current state-of-the-art for the material compatibility of vessels for the sampling of CO₂ for CCUS (<https://zenodo.org/records/8421721>), 3) literature survey on commercially available cylinders for the preparation of PRMs for CCUS (<https://zenodo.org/records/8421450>) and 4) protocol for the preparation of binary mixture of pure amine and CO₂ (<https://zenodo.org/records/11119890>).

Outcomes for the metrology and scientific communities

NMIs and DIs will develop Primary Standards for flow metering, gas analysis, physical property measurement and leak detections specifically which can be used to develop new Calibration and Measurement Capability (CMCs) to support national traceability for these measurements in CCUS. Furthermore, these new capabilities can be utilised by other measurement or calibration laboratories to provide their own calibration services for the CCUS community.

Laboratories, research organisations and academia will be able to use the new capabilities developed by NMIs, DIs and the other research participants in this project in order to perform high quality research within the CCUS area. The measurements will be traceable to the SI and suitably accurate so that the results obtained will support the development of new CCUS technologies.

The project will perform fundamental scientific work in the development and uncertainty evaluation of equations of state for CCS conditions.

Outcomes for relevant standards

The consortium will promote the results of the project within the standardisation community and will provide input into the standardisation process (ISO, CEN). For ISO, the standards relevant to the project that are in preparation/revision are identified, and the work on these standards will be suggested to the appropriate working groups or committees. There are plans to establish a new European working group dedicated to CCUS within CEN over the next few years, and the work from this project will greatly support the development of new standards within this working group.

The deliverables of this project are expected to directly support development or revision of standards within ISO/TC 265. The following ISO standards and New Work Item Proposals from ISO/TC 265 include measurements that will be studied in this project, and can be improved through this project, during the next revision: ISO 27913:2016 - Carbon dioxide capture, transportation and geological storage - Pipeline transportation systems, ISO 27914:2017 - Carbon dioxide capture, transportation and geological storage - Geological storage, ISO/TR 27915:2017 - Carbon dioxide capture, transportation and geological storage - Quantification and verification, ISO/TR 27921:2020 - Carbon dioxide capture, transportation, and geological storage - Cross Cutting Issues - CO₂ stream composition, ISO/TR 27922:2021 - Carbon dioxide capture - Overview of carbon dioxide capture technologies in the cement industry, and NWIP (approved June 2021) - Performance Index and Standard Test Method of Absorbent Performance for CO₂ Capture.

Longer-term economic, social and environmental impacts

Economic impact

The work of this project will support the flow metering, emissions monitoring, purity analysis and physical property measurements performed directly by CCUS operators.

Flow metering of carbon dioxide is required for monitoring emissions for CCS processes according to the EU Emissions Trading System (ETS). Inaccuracies could lead to errors in the calculations, which could either lead to overcharging of carbon emission costs or fines for providing inaccurate information.

The work of this project will support the monitoring of leaks in pipelines. The early identification of leaks will reduce the risk of extensive damage/loss of CO₂.

Impurities in carbon dioxide if not monitored can provide problems to the CCUS operator through unintended toxic releases, and corrosion or damage to pipelines, equipment and storage sites. These incidents can be costly. Firstly, they will require the operator to stop operation, but there would also be considerable costs for maintenance, repair and equipment replacement.

The work of this project will support CCUS operators, particularly for reducing operational costs. Impure carbon dioxide in CCS processes (e.g. inert gases at volume percent level) can increase energy requirements (for compression) which would inherently increase the cost of operation.

An inaccurate equations of state model (or the lack of one) may lead to issues with meeting CCUS operator conditions by not being able to monitor real physical properties. This could lead to dangerous scenarios for operation such as over-pressurisation or even cases where pure hydrogen could bubble out from the CO₂ and come into contact with pipelines.

Social impact

Developing new capability to monitor for carbon dioxide leaks is imperative for ensuring health and safety in the gas industry and it will protect citizens.

A focus will be made to educate new players (e.g. laboratories and instrument manufacturers) entering the CCUS market on the importance of laboratory accreditation and showing competency through comparisons, either for purity analysis or for the performance of online analysers. This will be a principle aim of the project.

Several technical seminars will be hosted by the participants to disseminate the newly developed standards and methodologies to allow fast uptake by commercial laboratories and organisations.

Several countries across Europe are running their own independent projects implementing CCUS technologies; however, this project will be the first time relevant industrial stakeholders from across Europe will join together in a collaborative effort to progress this topic.

The project, through hosting a website, organising seminars, presenting at conferences and running a Stakeholder Advisory Board will inherently support better networking between gas distribution networks, and the relevant laboratories and instrument manufacturers.

Environmental impact

CCS contributes to reductions of carbon dioxide emissions which support countries to meet targets set by the Climate Change Act. The activities within this project will not only support CCS for decarbonising gas, but all CCS processes including those used in tandem with power production and the direct extraction of carbon dioxide from the air. Many of the measurement requirements specified in this project originate from mandatory legislation, such as the EU ETS or national legislation (that may reference International Standards). Where legislation has not yet been developed, this project will support its development by ensuring the relevant measurement capability is already available.

The direct environmental impact from the metrological infrastructure, methods and guides generated from this project is as follows:

- The entire project is focused on supporting the success of European companies in implementing CCUS technologies; doing so will support the significant decrease in CO₂ emissions from industrial and energy processes or by direct air capture.

- Companies will have the ability to accurately measure carbon dioxide in CCS processes to track their carbon dioxide emissions in accordance with the EU ETS.

The potential future uses of the project are as follows: Calibration facilities for gaseous CO₂ developed in the project will help the CCUS industry to obtain accurate CO₂ flow measurements within the uncertainty requirements of specifications to monitor flow in delivery systems and also for leak monitoring. The project will validate commercial techniques for monitoring and quantifying CO₂ leaks from equipment and CCUS infrastructures such as pipelines but also CO₂ leaks from storage sites. This will help the CCUS industry use leak monitoring equipment with confidence and reduce the risk of extensive damage and loss of CO₂. Primary reference materials for impurities in CO₂ will be developed. These materials can be used to calibrate online and offline measurement systems for CO₂. The use of primary reference materials and accurate gas analysis methods will help the CCUS industry and laboratories to perform accurate purity measurements for CO₂. Furthermore, the project will set up experimental measurements to determine the physical properties of CO₂ in a mixture with capture solvents and validate equations of state to support the CCUS process and flow metering. This will lead to better understanding of the effect of impurities on the behaviour of CO₂ to ensure efficient and safe usage of the CCUS technology.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
Coordinator: Iris de Krom, VSL		Tel: +31152691754
Project website address: www.metccus.eu		E-mail: idekrom@vsl.nl
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. VSL, Netherlands	11. Air Liquide FuE, Germany	
2. CMI, Czechia	12. DNV, Netherlands	
3. DFM, Denmark	13. DTU, Denmark	
4. FORCE, Denmark	14. GERG, Belgium	
5. INRIM, Italy	15. NOVA, Portugal	
6. IPQ, Portugal	16. RUB, Germany	
7. JV, Norway	17. SINTEF ER, Norway	
8. PTB, Germany	18. UNITO, Italy	
9. RISE, Sweden	19. UVa, Spain	
10. VTT, Finland		
Associated Partners:		
20. NEL, United Kingdom		
21. NPL, United Kingdom		

Publishable Summary for 21GRD07 PlasticTrace

Metrological traceability of measurement data from nano- to small-microplastics for a greener environment and food safety

Overview

PlasticTrace aims to address the urgent need for the development and harmonisation of methods for the chemical identification, physical characterisation and quantification of released small micro/nanoplastics (SMPs/NPs) in drinking water, food and environmental matrices, as required by the EU's Circular Economy Action Plan (CEAP). In this context, hyphenated and complementary analytical approaches will be developed, optimised, compared and harmonised, leading to the establishment of metrological traceability of measurements through inter-laboratory comparison validation studies. Novel and environmentally relevant SMP/NP reference materials are being developed within the project (e.g. Polyethylene terephthalate (PET), Polyethylene (PE)). This will support the formation of a European metrology network through international cooperation with key stakeholders such as EURAMET's European Metrology Networks (e.g. "Network for Safe and Sustainable Food" and "Pollution Monitoring"), standards developing organisations (e.g. ISO TC 229, ISO TC 61, and CEN TC 249) and end users (e.g. food and drink producers, environmental monitoring programmes and health experts).

Need

Plastic pollution is recognised as a severe anthropogenic issue globally, where complex physico-chemical transformation processes (such as aging, degradation and fragmentation) producing MPs and, subsequently, NPs. These processes occur during production, consumer use, waste processing, as well as through environmental process after vehicles/industrial emissions. Several studies have reported the occurrence, analytical methods and toxicity of larger MPs (>100 µm) in the environment and food matrices. However, MPs (< 100 µm SMPs) and NPs (< 0.1 µm) in natural systems have been overlooked, primarily due to significant methodological challenges associated with their micro- and nano-specific properties.

To improve this gap, the European Commission (EC) commissioned a study focused on the potential ecotoxicological impacts of smaller plastic particles (SMPs/NPs), encouraging research aimed at a more accurate characterisation of both materials and exposure conditions. The need for efficient and reliable measurement infrastructure is required in support of (i) the European Chemicals Agency (ECHA)'s proposed restriction targeting intentionally added MPs in consumer products, (ii) the Marine Strategy Framework Directive (MSFD) which requires specific thresholds for litter types after harmonisation of the methodology, (iii) the new Drinking Water Directive (DWD) that mentions MPs explicitly, and (iv) the new Circular Economy Action Plan (CEAP) adopted in March 2020. In particular, the CEAP promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented. However, to support the CEAP and reduce plastic contamination, methods for SMP/NP identification in food and environmental matrices are needed. These methods need to be metrologically validated using appropriate reference materials to establish harmonised and traceable measurements of SMPs and NPs.

End users of the procedures to be developed include public organisations / non-governmental organisations (NGOs) dealing with environmental and food monitoring, regulatory bodies responsible for the control of environmental pollution and food safety, as well as industries potentially responsible (directly or indirectly) for MP emissions and disposal into the environment or the human food chain.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
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Issued: June 2024

Objectives

The overall aim of this project is to develop international metrological capacity that enables the traceable measurement and characterisation of SMPs and NPs in environmental and food samples and the production of suitable reference materials, according to the metrological requirements.

The specific objectives are:

1. **To develop pristine SI-traceable reference materials for SMPs (0.1 μm - 100 μm) and NPs (< 0.1 μm),** representative of partially degraded/naturally aged samples in complex food and environmental matrices. Realistic polydisperse size distributions and irregular shapes will be investigated.
2. **To develop accurate and efficient sample preparation methods for the measurement of SMPs and NPs in complex food and environmental matrices** (drinking and surface water, sewage sludge and milk). Such methods will include (i) enrichment prior to analysis, (ii) selective removal of natural background organic/inorganic matter, (iii) size fractionation/isolation, and (iv) homogenisation and partition steps. The sample preparation methods will be optimised to demonstrate a negligible effect on the particle characteristics and polymer compositions of samples.
3. **To develop accurate and robust methods** for the (i) characterisation of chemical identity of the SMPs/NPs polymer type; (ii) physical particle characterisation and quantification, size distribution and particle morphologies; and (iii) quantification of the mass fraction in complex matrices.
4. **To demonstrate the validity and applicability of the methods and reference materials developed in Objectives 1-3 via an inter-laboratory comparison.** As part of the comparison, best practice guidance on the traceable measurement and characterisation of SMPs and NPs in food and environmental matrices will be developed.
5. **To facilitate the take up of the technology and measurement infrastructure** developed in the project by the measurement supply chain, appropriate EURAMET's European Metrology Networks, relevant associations outside of Europe (e.g. National Nanotechnology Initiative USA), standards developing organisations (e.g. ISO TC 229, ISO TC 61, CEN TC 249 and those associated with the Urban Waste Water Treatment Directive (91/271/EU), the Marine Strategy Framework Directive (2008/56/EC) and the Drinking Water Directive (EU) 2020/2184) and end users (e.g. food and drink producers, environmental monitoring programmes and health experts).

Progress beyond the state of the art and results

Development of SI-traceable reference materials for SMPs (0.1 μm - 100 μm) and NPs (< 0.1 μm)

SMP/NP reference materials representative of partially degraded/naturally aged samples are currently not available and will be developed and provided by PlasticTrace. Candidate SMP/NP Reference Materials (RMs) representative of real plastic particles found in food and the environment will be developed in accordance with their relevant types, shapes, sizes and ageing status. Particle sizes are produced according to the infrastructure capacity and the toxicological relevance with two primary categories: (i) 100 - 10 μm and (ii) < 10 μm . To increase environmental relevance, some of the RMs will be aged.

The decision for the first untreated and degraded polymer types was made based on the literature review and background exchange with previous projects (EU and JPI Oceans funded projects POLYRISK (ID: 964766), PlasticsFatE (ID: 965367) and ANDROMEDA). Polyethylene terephthalate (PET) and artificially UV-weathered Polyethylene (PE) were selected. Both PET and PE are often in contact with food and beverages. Both are also found as plastic litter in the environment. Densities of PET and PE polymers are both lower and higher than 1 g/cm³, thus representing polymers that float or sink in water. Within PlasticTrace bottle-grade PET granules and aged PE film were cryomilled in a centrifugal and ball mill to produce particles with polydisperse size distribution and irregular shape imitating environmental SMP/NPs. The produced powder was sieved with a 100 μm stainless steel ring sieve to obtain particles < 100 μm .

From this reference material candidates containing small microplastic particles (SMPs) of PET (10-100 μm) with limited mass and low particle numbers in form of water-soluble tablets were developed and characterised for mass and particle numbers. The material was homogenous and stable according to mass using Py-GC/MS

and TED-GC/MS, as well as for number-based methods such as Raman spectroscopy. Cumulative particle numbers and size distribution down to particles $> 20 \mu\text{m}$ were similar between tablets in an internal validation study. Comparable results on particle numbers were also achieved with μFTIR and LDIR techniques down to particles $> 50 \mu\text{m}$ due to the lower spatial resolution. The tablets are water-soluble and can directly be used on the filter or dissolved separately before analysis.

Representative nanoplastics candidate reference materials were produced by top-down approaches according to literature (Hildebrandt, Macromol. Rapid Commun., 2023 DOI: 10.1002/marc.202200874). More than 800 glass vials were produced each containing this material in 2 ml water. To increase the speed of the production process and maintain a polydisperse distribution of the particles, filtration was performed to remove the large ($> 1 \mu\text{m}$) polymer fragments without reducing the polydispersity index. PE (Polyethylene) and PP (Polypropylene) nano material was produced by crushing PE or PP pellets in acetone with followed by sieving/filtration before changing of the solvent to water. All obtained nanoplastics are in form of suspensions. The main characterisation methods used were dynamic light scattering and particle tracking analysis supplemented by scanning electron microscopy (SEM), atomic force microscopy (AFM) and Raman spectroscopy. Homogeneity and stability studies were also performed, mainly in terms of particle number concentrations and average hydrodynamic size, demonstrating a convincing fit for purpose inter-bottle uncertainty. These contain polyethylene (PE) or polypropylene (PP) particles ($< 1 \mu\text{m}$) with irregular and fragmented shape, broad size distributions and defined particle numbers. According to the hydrodynamic size distribution, PP and PE nanoplastic materials have an average hydrodynamic size of about 150 nm and 125 nm, respectively, with at least a 27 % (PP) and a 50 % (PE) size fraction lower than 100 nm. All prepared SMP/NP RMs were tested for homogeneity and stability control according to ISO GUIDE 35:2017(E).

Development of accurate and efficient sample preparation methods for the measurement of SMPs and NPs in complex food and environmental matrices

The identification and the analysis of SMPs/NPs in complex media is very challenging due to the inability to readily distinguish SMPs/NPs from other types of particles in the same size range (dissolved and particulate organic matter) and due to the need for pre-concentrating samples to meet the detection limits for their identification. The existing procedures for sample preparation are often critical in terms of the stability of very small and aged particles, as well as very time consuming. The project will cover the application and harmonisation of procedures such as the application of state-of-the-art digestion protocols for complex organic media, the selection of specific enrichment procedures suitable for each analytical approach, the development of filters in the sub-micron/nanometre range for SMPs/NPs filtration, and the application of different types of innovative fractionation steps for size separation.

Four types of matrices, i.e. drinking water, milk, surface water and sewage sludge, were selected as relevant environmental and food matrices for MP contamination, exposure and human consumption. Matrix from a river system has been collected and subjected to a basic characterisation before distribution to the partners. The matrix consists in a powder made by suspended particulate matter (SPM). SPM characterisation was mainly performed for size distribution by laser diffraction and XPT, carbon content through total organic carbon analysis and thermo-gravimetric analysis (TGA), elemental composition through ICP-MS/MS, to assess their homogeneity. In order to reduce the matrix, a series of tests were done with oxidative digestion (H_2O_2 30 %) together with density separation strategies for the final implementation of the SOPs. Spiking experiments are in progress for the optimisation of the SOPs for both thermo-analytical and spectroscopy-based methods in order to evaluate particle recovery and methods sensitivity.

Baby milk powder as well as bottled water was purchased from local supermarket near each of the participant's laboratory, considering the same composition. Basic characterisation through thermogravimetric analysis (TGA) and elemental composition through ICP-OES was also performed. Different SOPs have been explored using alkaline treatment (TMAH at 25 %, 10 % and 5 %) together with enzymatic digestion, oxidative (H_2O_2 30 %) and acidic (Citric acid 15 %, 10 %, 1 %) treatment to reduce the organic component of the milk powder. In both approaches, i.e. number-based and mass-based methods, PET tablets were used for the spiking experiment and to evaluate the effect of the sample treatment on particle shape, size and concentrations. Regarding the mass-based approach by TED-GC/MS, citric acid's test has been successful regarding both matrix reduction $> 99 \%$ and recovery rate when the matrix was spiked with PET tablets. A preliminary SOPs for the TED-GC/MS will be soon uploaded on Zenodo repository.

As for plastic particles lower than 10 μm , a stakeholder consultation regarding relevant concentration levels and characterisation approaches of SMPs and NPs in food matrices has been conducted. Development of sample fractionation strategies has started using AF4 and pristine PP < 200 nm. Preliminary data suggest that it is possible to separate NPs with sizes < 0.1 μm using this approach. Additional experiments testing CF3 are in progress for the separation of the provided nanoplastics. Work aiming at development and optimisation on spiking protocols has started using nanoPP material on both bottled drinking water and milk.

This will provide an opportunity to further develop online and offline methods for particle size distribution analysis, stability evaluation, polymer identification by spectroscopic tools and mass fraction quantification by thermos-analytical techniques.

Development of accurate and robust methods for the characterisation of SMPs/NPs

Given the challenge of characterising SMPs/NPs in complex matrices, the project will have two primary focus areas: (i) development and harmonisation of routine/established analytical methods (μFTIR , μRaman , EM, Pyr- GC/MS, TED-GC/MS), including sample preparation for the measurement of SMPs (100-10 μm) in food and environmental related samples, and (ii) development of innovative hyphenated, complementary and correlative analytical approaches for the measurement of SMPs/NPs in drinking water and milk samples.

In particular, the following beyond the state of the art measurement capabilities will be developed and optimised:

- (i) Light scattering methods for the characterisation of size distribution and particle number with hyphenated approaches based on fractionation techniques;
- (ii) Innovative micro-spectroscopy methods for fast automation and data processing for large scale plastic particle monitoring and a new online hyphenated prototype based on fractionation-sizing-quantification and chemical characterisation;
- (iii) Mass spectrometry-based methods for the characterisation of mass concentration, number and chemical identification with hyphenated approaches based on fractionation techniques;
- (iv) High-resolution, correlative and automated microscopy methods for the characterisation of size distribution, shape and chemical identification performed on fractionated or filtered samples.

A hyphenated approach was developed in this context by the combination of asymmetric flow field-flow fractionation (AF4) for NPs separation and quantification through a UV detector, μRaman spectroscopy enabled by dielectrophoresis for NPs chemical identification, and DLS for size determination. This approach demonstrated to be suitable for the characterisation of plastic particle down to 65 nm, and further resolve relative concentrations of binary mixtures of different types of nanoplastics with similar size using a validated chemometric tool.

Validity and applicability of the developed methods and reference materials

The project works closely together with several interlaboratory comparison studies ILC where material from the project was used after homogeneity and stability has been thoroughly evaluated in accordance with ISO GUIDE 35:2017(E). The project is working closely together with VAMAS, QUASIMEME and ISO on ILCs to ensure not only the involvement of the consortium but also the wider laboratory community and close cooperation with regulatory bodies. In this context the project has transferred new knowledge and materials to ISO/TC 147/SC 2/JWG 1 by supporting the ILC trial for the validation of ISO 16094-2 standard "Water quality — Analysis of microplastics in water – Part 2: vibrational spectroscopy methods for waters with low content of suspended solids including drinking water". PET Tablets produced in the project were selected as reference materials by the ILC Organizing Committee for the validation of the present methodology and distributed to the selected participants worldwide. Moreover, the project actively contributed to the "Project 2: Interlaboratory Comparison on detection and quantitative assessment of microplastics by use of spectroscopic and thermo-analytical methods", which was organised within the VAMAS TWA 45 "Micro- and Nano Plastics in the Environment" where more than 50 participants worldwide were encountered. This will be combined with a feasibility study directed to the certification process of the reference materials and will eventually lead to characterisation of a selected food and/or environmental sample materials spiked with SMPs and NPs, to support the validation and harmonisation of the developed methods, as well as to provide reliable quantitative data that contribute directly to the development and implementation of future management strategies. Together with the NORMAN network an activity will be developed on the calibration of spectroscopic instruments and identification software using so called sandwich filters containing a well-defined number of MPs.

Outcomes and impact

To maximise the impact of the project, all activities are continuously disseminated and communicated through the project's website (www.plastictrace.eu) and LinkedIn (www.linkedin.com/company/92810943) (These are the preferred platforms to effectively reach stakeholders, partners and others interested in the research and project overall in addition to workshops). Furthermore, several newsletters have been distributed to partners, stakeholders, on social media and to the broader scientific community every 6 months. A stakeholder advisory board consisting of 22 key stakeholders supports the project and further interaction with a larger number of expert practitioners, the standards community, and metrology institutes is done through workshops. Joint EU project meetings to exchange knowledge and synchronise activities with on-going EU projects are integrated in several activities and the project is represented at advisory boards of several of relevant projects. Results have been presented at 47 scientific national and international meetings and symposia, and published in popular scientific literature. Consortium participants are actively taking part in standards and technical committees and working groups to disseminate the outcomes from the different activities of the project especially. Training of technical staff is crucial and will be accomplished by capacity building workshops, an e-Learning program of which the first three modules are recorded, and a training network.

Already two stakeholder workshops were organised on the topic "Measurement needs for Microplastics" at INRIM in connection with VAMAS Technical Working Area 47th SC Meeting, but also a Stakeholder Advisory Board meeting was organised in connection with the first project meeting. In addition, the stakeholders were asked in two questionnaires to advice on preferred reference materials and analytical methods. The project has also joined several EU projects meeting, such as EUROqCHARM and COST Action PRIORITY on nano- and microplastic standardisations. The project has also organised special sessions with the NORMAN network and the general assembly, in addition with Plastics Europe in collaboration with CUSP and NORqCHARM to present the activities of the project on European harmonisation. Additionally, the project has participated in several events, such as World Cafés with other ongoing EU Horizon projects, including Plasticsfate and the Norman network. The Project has also been active in several standardisation activities, to inform standards bodies and committees the development and results of the project to be incorporated into standards, such as with international standards development organisations (ISO, CEN, DIN) and metrology committees (BIPM and CIPM).

Outcomes for industrial and other user communities

The project will provide application-oriented analysis tools, as well as an infrastructure for SMPs/NPs measurement across various fields. The establishment of a traceable measurement chain, with the provision of new reference materials and associated methods, will improve the reliability and accuracy of SMPs/NPs characterisation, and thus supporting utilisation of the results by end users (accredited commercial laboratories, national environmental institutes, and monitoring agencies). Together with tools for quality control and proficiency testing, the traceability will guarantee standardisation and comparability of the results, currently lacking for SMPs and especially NPs. All will be supported by 9 eLearning modules to facilitate implementation of the results from the project. The outcome of the project will enable comparable and traceable monitoring to support decision-making and effective assessment of mitigation measures implemented by the EU's Plastic Strategy.

Outcomes for the metrology and scientific communities

PlasticTrace will provide validated SI-traceable measurement capabilities for the integral quantification of SMPs/NPs derived from the most common polymers, which is currently not available. It will also provide efficient sample preparation SOPs for relevant complex environmental and food samples, which will support both the measurement infrastructure (aimed at routine laboratories) and the academic scientific community. New technological developments in innovative hyphenated, complementary, and correlative analytical approaches and their standardisation will represent major outcomes from the project, to be quickly adopted into common use by metrological, research and scientific communities. These new and innovative methods and technologies not only have a significant potential for high-impact publications in high-ranking scientific journals in both the environmental, food and metrological fields, but also direct implementation of the standardised methods to measure SMPs/NPs within ongoing and future scientific and research projects.

Outcomes for relevant standards

Several project participants are represented internationally in several ISO/CEN committees and working groups in VAMAS and BIPM, as well as national standardisation organisations (DIN, AFNOR, SFS, Standard Norway). This will guarantee the implementation of the project results in standardised methods both at a national and international level. The project will contribute to the validation of the ISO method for MP in water samples (ISO NP 16094) and sediment (CEN/TC 444/WG 6/TG). In turn, this will build capacity for European environmental, food and drinking water monitoring programmes on SMPs/NPs. In line with the EU strategy and action plans, several EU directives are currently being revised or updated to include SMPs/NPs. This includes (i) the Urban Waste Water Treatment Directive (UWWTD), in which the MPs are currently not included and which is under revision since 2022, (ii) the Sewage Sludge Directive (SSD) which has signalled similar needs, (iii) the Environmental Quality Standards Directive (EQSD) where inclusion of MPs is currently being discussed, and (iv) the Marine Strategy Framework Directive (MSFD) which is currently discussing threshold values that need to be measured and controlled. Concerning food, no regulation on SMP/NPs is currently being considered due to the lack of harmonised analytical methods, but the European Commission sees a critical need in this field. In addition, the Drinking Water Directive (DWD) will adopt a methodology for measuring MPs in drinking water by adopting a legal binding delegated act(s) by January 2024. The results of PlasticTrace will represent a crucial contribution towards achieving the objectives of these standards and directives on the restriction and especially control of SMP/NPs.

Longer-term economic, social, and environmental impacts

PlasticTrace will address major societal needs defined in the EU Framework Programme for Research and Innovation 2021–2027, particularly in Horizon Europe Cluster 6, and by the CEAP. These directives highlight the severe impact of chemical pollutants and MPs on the health of water bodies and the need to develop harmonised measurement methods for unintentionally released SMPs/NPs and their risk in the environment, drinking water and foods. Reliable SMPs/NPs analytical determination is a prerequisite to address major knowledge gaps, and to provide a framework for science-based risk assessment and consequent adoption of measures tackling plastic particle distribution and accumulation in the environment and food with potential long-range public health, economic and social impacts.

List of publications

1. Barzan, Giulia et al (2024) 'Development of innovative antioxidant food packaging systems based on natural extracts from food industry waste and Moringa oleifera leaves', Food Chemistry, 432 p. 137088. Available at <https://doi.org/10.1016/j.foodchem.2023.137088>
2. Ilchenko, Oleksii et al (2024) 'Optics miniaturization strategy for demanding Raman spectroscopy applications'. Nat Commun 15, p. 3049. Available at <https://doi.org/10.1038/s41467-024-47044-7>
3. Gerace, Mathias Hanson, Sørensen, Lisbet, Booth, Andy M. (2024) 'Small micro- and nanoplastic test and reference materials for research: Current status and future needs', Cambridge Prisms: Plastics, 2(e13) p. 1-12. Available at <https://doi.org/10.1017/plc.2024.13>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 October 2022, 36months
Coordinator: Andrea Mario Giovannozzi, INRIM Tel: +39 011 3919330 E-mail: a.giovannozzi@inrim.it		
Project website address: https://plastictrace.eu/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRIM, Italy	11. FC.ID, Portugal	20. HF, France
2. BAM, Germany	12. FhG, Germany	21. Nestlé Waters, France
3. DFM, Denmark	13. Hereon, Germany	22. SmartMembranes, Germany
4. IHi, Portugal	14. Postnova, Germany	
5. IPQ, Portugal	15. Sciensano, Belgium	
6. LNE, France	16. SINTEF, Norway	
7. NIVA, Norway	17. UDC, Spain	
8. SMD, Belgium	18. UNIPR, Italy	
9. SYKE, Finland	19. UNITO, Italy	
10. UBA, Germany		
Associated Partners: 23. LGC, United Kingdom		

Publishable Summary for 21GRD08 SoMMet Metrology for multi-scale monitoring of soil moisture

Overview

Water and soil are vital resources that are seriously affected by climate change and degradation. Water at the land surface, primarily in the form of soil moisture, is a key resource influencing agriculture, forestry, groundwater recharge, weather, climate, and greenhouse gas emissions. Several soil moisture observation systems exist on multiple scales, but they need to be harmonised. The overall objective of this project is to develop novel metrological tools and establish a metrological foundation for soil moisture measurements on multiple lateral scales, ranging from decimetre to kilometre, ensuring the traceability and harmonisation of the various soil moisture measurement methods.

Need

Soil moisture is one of the Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS) of the World Meteorological Organisation (WMO). Soil moisture influences the land-atmosphere interactions on both weather and climate timescales. Long-term carbon storage and release in soil is strongly influenced by soil moisture - only a healthy and adequately moist soil can act as carbon sink in the strategies for greenhouse gases reduction and adaptation to climate change impacts. Soils are a cross-cutting theme within the European Green Deal (EGD), communicated by the European Commission in 'EC COM/2019/640 final', as the sectors of water management, agriculture, forestry, and biodiversity are inherently interdependent.

Soil moisture measurements at point scales, performed by practical users in agriculture and hydrology or by scientists dealing with soil moisture as an ECV, are not representative of the soil moisture at the larger scales that are relevant for practical applications. Point scale measurements use physical tactile sensors which are invasive and subject to local issues. To overcome this, complex sampling designs and interpolation methods can be implemented, however uncertainties need to be improved and practical calibration guidelines developed. Remote observation of the Earth can be used for real-time and continuous assessment of soil moisture on the kilometre-scale however intermediate scale soil moisture methods such as cosmic-ray neutron sensing (CRNS) are needed so that gap from point scale to remote sensing can be bridged. The CRNS methodology needs to be harmonised and reliable calibration, validation and characterisation methods developed.

There is an overall need for comparison and harmonisation of soil moisture observations at different spatial and temporal scales based on different methods. Furthermore, 'the next logical step' is needed, i.e., performing the data fusion of the multi-scale soil moisture measurements to generate high-quality, temporally, and spatially consistent soil moisture information, useful for land surface sciences and applications, such as climate observations, weather forecasting, hydrology, and agriculture.

Objectives

The overall aim of this project is to develop novel and traceable methods and establish a metrological infrastructure for soil moisture measurements covering lateral scales ranging from the decimetre to kilometre.

The specific objectives of the project are:

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

1. To develop metrological framework, including primary and secondary transfer standards, to ensure SI-traceable point-scale soil moisture measurements with uncertainties of 5 % under laboratory conditions. To develop metrological framework for validation of existing cosmic-ray neutron sensing (CRNS) devices, currently available in the market, under laboratory conditions.
2. To develop new validation practices for cosmic-ray neutron sensing (CRNS) methodology for use in outdoor conditions. This includes the application and validation of neutron transport models used to interpret CRNS detector signals specific to the soil moisture measurand, and the standardisation of the CRNS on-field calibration procedure for soil moisture assessment on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre.
3. To investigate the constraints and accuracy of soil moisture measurement methodologies using intercomparison campaigns on local and remote sensing. In addition, to develop procedures, summarized in good practice guides, to overcome (i) temporal and spatial differences regarding the sensing domains of soil moisture measurement methods and (ii) the influence of other state variables such as air humidity and soil temperature affecting the measurements.
4. To develop a multi-scale metrological system and metrologically traceable methods for soil moisture monitoring, covering lateral scales ranging from 10^{-1} m to 10^3 m and to depths of up to 1 metre and temporal scales ranging from hours to days, to assess the soil moisture with traceable relative uncertainty of 20 % or better. This includes the development of a cross-disciplinary harmonisation system on the medium sub-kilometre-scale and the establishment of (i) metrological traceability of soil moisture measurements using point-scale sensors (from Objective 1) and satellite measurement techniques and (ii) fit for purpose modelling. In addition, to develop techniques to support the harmonisation of soil moisture assessment.
5. To cooperate with user communities to define design criteria for emerging and future hydrological and meteorological/climatological soil moisture networks using the combination of point-, intermediate- and large-scale methods. To cooperate with the European Metrology Network for Climate and Ocean Observation (EMN COO) and relevant international organisations (e.g., WMO) to facilitate the dissemination of the project outputs.

Progress beyond the state of the art and results

Several soil moisture observation systems have been developed, ranging from invasive point-scale soil moisture sensors to large-scale remote sensing products. In addition, more recently, a non-invasive intermediate scale soil moisture method, cosmic-ray neutron sensing (CRNS) has found widespread use. Despite several initiatives, no harmonisation approaches under metrology standards are available. This project will address this gap by developing the metrological tools needed for traceable and validated soil moisture measurements. For the first time, metrological tools for all three domains/scales will be considered in a holistic approach, to harmonise soil moisture monitoring across scales.

Metrologically traceable methods for multi-scale soil moisture measurements: New traceable methods for the measurement of soil moisture in outdoor conditions on lateral scales in the range of 10^{-1} m to 10^3 m with relative combined uncertainty of 20 % will be developed. To achieve this, new standards and methods for the traceability of the point-scale soil moisture measurements under laboratory conditions are under development (at the facilities of project participants DTI, TUBITAK and CMI). Later, the measurement supply chain will be extended to outdoor conditions by transfer standards and an improved on-field sampling method. The calibration procedures for point-scale sensors, as they are being used in different communities, have been reviewed from the SI-traceability perspective. The SI-traceability scheme has been set out for the measurement of moisture in soil samples under laboratory conditions. The primary reference setup of DTI, which was previously developed in the framework of the EMRP project SIB64 METefnet for determination of moisture in solid samples, but not in soil samples, was adapted specifically for soil moisture measurements. The setup is now being commissioned and validated in laboratory with various soil samples. The transfer (secondary) standard, based on loss on drying (LoD) method, has been designed and is currently under construction. An interlaboratory comparison of the different reference methods is planned. The primary and secondary reference setups will make it possible to carry out the SI-traceability chain from the laboratories to the outdoor conditions.

New traceability scheme and validation practices for CRNS method: A traceability scheme for CRNS methodology is currently under development. The validation of the CRNS systems models and their neutron response functions is currently in progress, using computing cluster-aided calculations and dedicated measurement campaigns in neutron reference fields. The existing facilities of the neutron metrology community have been reviewed from the perspective of usability for the specific needs of the SI-traceable validation and characterisation of the instruments used in the CRNS methodology. The state-of-the-art CRNS instruments, currently available on the market which are being used in existing and emerging CRNS networks, have been reviewed and three different types of CRNS devices were selected to be characterized and investigated in the project in detail. The CRNS devices are modelled using suitable Monte Carlo-based radiation transport codes. The SI-traceable measurement of neutrons in the neutron metrology laboratories makes it possible to validate these models. In the next step, the neutron response functions will be calculated based on the validated models. This will allow for an effective validation of current and upcoming CRNS system designs. The combination of metrology for neutron radiation and metrology of temperature and humidity will allow, for the first time, a traceable benchmarking of CRNS devices under outdoor conditions, leading to new validation practices. There will be improved understanding of the CRNS footprint (sensing volume), of systematic effects, and of the uncertainty of the soil moisture retrieval.

New on-field comparison campaigns on local and remote sensing: New soil moisture data are systematically collected at established experimental field sites, operated by participants, and selected according to their relevance for the calibration and validation practices of soil moisture retrieval by CRNS and remote sensing. This data will be a clear improvement over previous historical data sets as they will be based on newly characterised devices of point-scale and CRNS methods, and the measurements will be designed for the purpose of harmonisation. The data will be used to investigate the limitations and accuracy of the individual methods. New approaches and methods will be developed to overcome the temporal and spatial differences regarding the sensing domains of the individual methods. Three high-level test field sites and two accompanying sites were selected. On the high-level test field site, systematic data taking is being planned with the three soil moisture measurement methods, namely with the point-scale sensors, the CRNS instruments, and the satellite-based remote sensing. A unified data retrieval and data processing system is in operation, enabling an automatic processing and feeding of the field data into the project's data storage and management system. The actual measurement campaigns of systematic soil moisture measurement on all three high-level test field sites are currently in preparation.

Cross-disciplinary harmonisation system for soil moisture monitoring: Based on the newly collected data sets, and on the historical time series, novel procedures for harmonising soil moisture assessments on different temporal scales and on lateral scales ranging from point scale to kilometre scale will be developed. New recommendations for the calibration and validation practices of the soil moisture retrieval by remote sensing, as well as new methodologies for data fusion, will be developed. Extensive literature studies were carried out to review and categorize the existing methods to characterize spatial and temporal soil moisture observations, the existing soil moisture harmonisation methods, as well as the state-of-the-art data fusion methods for soil moisture estimation at different spatiotemporal scales. The input from the project's Stakeholder Committee was received as well. This gathered knowledge is now the starting point for the activities that will build upon the new soil moisture data collected within the project.

Outcomes and impact

The project created a Stakeholder Committee (SC) consisting of soil moisture experts from various communities, including representatives of the European Space Agency, the experts leadingly involved in the International Soil Moisture Network, the Land Product Validation Subgroup of the Working Group on Calibration and Validation of the Committee on Earth Observation Satellites, experts on soil moisture products from remote sensing and experts on hydrology, soil physics and (agro)meteorology. The SC grows further as the consortium promotes the project to communities such as manufacturers of the meteorological equipment. A valuable input was obtained from the SC on the needs for metrology support of the various interested parties. Links to other projects, networks and national meteorology services dealing with soil moisture assessment have been established. The consortium participated in several conferences to promote the project and has engaged with experts from the relevant communities. A stakeholder survey was carried out and valuable feedback was obtained. Furthermore, an information exchange meeting was held on metrology principles and open issues of soil moisture measurement on multiple scales. This event improved the understanding between metrology and non-metrology communities and increased the awareness of the project.

Outcomes for industrial and other user communities

The calibration procedure developed in this project will allow manufacturers of hydro-meteorological equipment to certify the performance of their instruments based on standard procedures. Manufacturers of laboratory equipment for instrument calibration will benefit from the project outcomes as well, since they will be able to provide compliant calibration devices for soil moisture instruments. This will enable them to market standardised and interoperable equipment and services that will underpin the harmonisation efforts in application areas such as weather monitoring and forecasting, and precision farming.

The project directly liaises with industrial stakeholders via the Stakeholder Committee (SC). The SC includes representatives from agro-meteorological services, national meteorological services, WMO members of expert teams, regional instrument centres, manufacturers centres, and is helping the project's results to directly impact such representatives. Based on the stakeholder survey and with the help of the SC members, contacts to various manufacturers of the meteorological equipment have been established, especially to the manufacturers of soil moisture measurement equipment. Their needs for metrological support and sound metrological foundation have become part of the project inputs. The benefits of the upcoming project developments have been communicated to these communities, and the active information exchange with them will remain a key part of the project's dissemination and communication strategies.

The intermediate project results, such as the tests and characterisations of the commercial CRNS systems in neutron metrology laboratories and the SI-traceability concepts for CRNS-aided soil moisture assessment, have been communicated to the entrepreneurial developers, as well as the users of these systems and sensor networks. The communication of project outcomes will continue further in 2024, e.g. at the 7th International COSMOS Workshop (September 2024 at Hillsborough, Northern Ireland) devoted to the transition of the CRNS technology from research to operations in hydrological and meteorological networks. In parallel, the intermediate results achieved so far in the metrologically-secured determination of the soil water content under laboratory conditions are being communicated to the sensors manufacturers.

Outcomes for the metrology and scientific communities

SI-traceable metrology for water content in materials has been partly established over the last decade. However, at present, no countries have BIPM Calibration and Measurement Capabilities for moisture measurement, and SI-traceable measurements of soil moisture on primary level have, to our knowledge, not been reported. One important outcome of this project is to establish primary-level soil moisture measurements with developed uncertainty budgets. The established metrological foundation for soil moisture measurement should allow traceable calibration and validation of secondary measurement standards such as those based on traditional loss-on-drying and of transfer standards.

For soil moisture measurement there are currently unresolved issues with appropriate transfer standards and sampling methods. This project will address these issues and the transfer of the metrological chain of traceability to outdoor conditions, using new transfer standards based on visible and near-infrared spectral reflectance measurements for on-site calibrations. This improved metrological basis will be used for improving the CRNS methodology and should have direct impact on networks in Europe and worldwide. Harmonised multi-scale soil moisture data, with reliable uncertainties, will improve hydrological modelling, climate and weather forecasting by ensuring better comparability between data sets obtained with different methods.

The project was promoted on several European-scale conferences of scientific communities dealing with hydrological/environmental observations, soil moisture harmonisation as well as monitoring and SI-traceable measurement of ionising radiation in environment. Alongside the CRNS system developer enterprises, the project results will be disseminated to the scientific communities that make use of the CRNS technology.

Outcomes for relevant standards

Currently, most of the guidance for soil moisture measurements in the field is contained in good practice guidelines, and there is a lack of relevant validation and standardisation. Standardised procedures based on suitable calibration devices would benefit manufacturers and users of soil moisture instruments. Indeed, their use is currently limited due to insufficient standardised calibration procedures and the lack of both metrological comparison and harmonisation among different sensor typologies and gravimetric/volumetric manual soil moisture measurements.

This project will support standardisation work for soil moisture measurements by providing a technical report to CEN TC444 Environmental Characterisation WG5 Physical tests for consideration and adoption as well as

to ISO TC-190 Soil quality WG1 Soil and Climate Change SC3 Chemical and physical characterisation for update of an existing standard. The project will also provide input to WMO Standing Committee on Measurements, Instrumentation and Traceability (WMO SC-MINT), WMO Commission for Observation, Infrastructure and Information Systems (INFCOM), WMO Commission for Instruments and Methods of Observation (CIMO) expert team on Operational Metrology, WMO Global Climate Observing System (GCOS) Surface Reference Network, WMO SC-MINT expert team on Measurement Uncertainty (ET-MU), EURAMET Technical Committee for Thermometry (TC-T) and BIPM Consultative Committee for Thermometry Working Group for Humidity (CCT-WG-Hu). The goal of the project is also to provide input to guidance material such as updates to the WMO 'Guide to Meteorological Instruments and Methods of Observation' (WMO Guide No. 8).

The project was promoted in various face-to-face meetings with metrology experts, in particular the project's consortium activities were presented to the plenary meetings of the EURAMET TC-T, TC-IR and the BIPM CCT-WG-Hu. The intermediate project results are regularly communicated to the committees' members. In September 2023, the SoMMet partner INRIM organised the international conference MMC 2023 (Metrology for Meteorology and Climate) in Torino, Italy that brought together the communities of metrology, meteorology, and geosciences experts. The project motivation and results were presented in a session dedicated specifically to the project. The multidisciplinary audience consisted of scientists, representatives and stakeholders from various organisations and sectors such as the WMO, the WMO GCOS, metrology of temperature and humidity, meteorological services, manufacturers of calibration equipment and of sensors for environmental monitoring. The discussions with the experts and their feedback to the SoMMet-focused presentations serves as the input for shaping further research works and the dissemination, communication and exploitation plans of the project.

Longer-term economic, social and environmental impacts

A wider impact of the project results is expected on companies operating in the fields of hydro-meteorological warnings, water resources management, flood control, agriculture and hydro-power plants. These companies provide services based on the monitoring of hydro-meteorological variables and the processing of the related measurements to support the final users' decisions about the configuration of industrial systems, even in real time. The use of calibrated soil moisture type instruments, in conjunction with the other meteorological observables, would improve the management capabilities of the users since decisions would be based on traceable measurements. With more reliable data it would therefore be possible to promptly inform the weather services, local agro-meteorology consortia and users, about the risk of drought and flood. The accuracy of such information is vital for the issuing of effective and timely warnings. This main economic impact would therefore be two-fold; an increase in trustworthy and timelier irrigation plans, with direct benefits on agricultural and farming production and reduction of water waste for irrigation and hence increased water availability.

Based on a general lack of traceability and data quality in historical observation, the Global Climate Observing System (GCOS) is preparing the creation of the GCOS Surface Reference Network (GSRN). Among the Essential Climate Variables prescribed by GSRN, soil moisture is one of the fundamental observed quantities for a reference site. The non-contact systems developed in the project will offer more reliable data and are a good candidate for long-term data series recording. In addition, this project is expected to have a substantial impact in climate science through the GCOS and other similar initiatives.

As stated above, the project was promoted, and its intermediate results were presented at the MMC 2023 conference in September 2023. The interaction with the stakeholder communities including the WMO experts and other organisations is being kept active to enable a direct flow of information throughout the duration of the project.

List of publications

- Gianessi, Stefano et al (2,024) 'Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation', Geoscientific Instrumentation, Methods and Data Systems, 13(1) p. 9-25. Available at <https://doi.org/10.5194/gi-13-9-2024>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

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1. PTB, Germany	10. CNR, Italy	
2. CIEMAT, Spain	11. CTU, Czech Republic	
3. CMI, Czech Republic	12. IAPAN, Poland	
4. DTI, Denmark	13. PoliMi, Italy	
5. INRIM, Italy	14. UFZ, Germany	
6. IRSN, France	15. UHEI, Germany	
7. JV, Norway	16. UNIBO, Italy	
8. SMU, Slovakia	17. UP DE, Germany	
9. TUBITAK, Türkiye		
Associated Partners: 18. UKCEH, United Kingdom		

Publishable Summary for 21GRD09 MetroPOEM

Metrology for the harmonisation of measurements of environmental pollutants in Europe

Overview

European Green Deal's ambition for zero pollution requires the development of highly sensitive techniques to detect ultra-low amounts of pollutants and to determine their isotope ratios. Mass spectrometry is a key method for determination of non-radioactive polluting elements and is of increasing importance for long-lived radionuclides. This project will bridge the gap between both methods and will establish new tools for tracing pollutants. Measurement uncertainties and detection limits will be significantly reduced using newly developed reference materials and SI-traceable measurement procedures with an immediate impact for tracking pollution sources by commonly available mass spectrometers.

Need

This project supports the strategies described by the upcoming European Metrology Network (EMN) on Pollution Monitoring (POLMO) and the established EMN on Radiation Protection (supporting the Basic Safety Standards directive). According to their strategies, there is a strong need to improve data quality for monitoring and reporting pollution in the air, water, and soil. In addition, the lack of suitable traceability chains and appropriate quality control compromises the comparability and robustness of measurements.

To detect radioactive isotopes and stable polluting elements in the environment, fast, sensitive and inexpensive analytical procedures are needed. Mass spectrometry techniques have a great potential to address this requirement. Despite the increasing application of single collector ICP-MS (Inductively Coupled Plasma Mass Spectrometry), this potential cannot be fully realised unless techniques can be validated with traceable multi-element reference materials. However, multi-element certified reference materials are usually not available and even single-element certified reference materials are limited to very few elements. Nevertheless, these reference materials are urgently needed to calibrate mass spectrometric measurements, due to mass bias effects occurring during the measurements in mass spectrometers.

The orientation document, issued by EURAMET's Ionising Radiation Technical Committee and the EMN on Radiation Protection, clearly described a metrological need for "*traceability of radionuclide concentration measurements in the environment*". This topic refers to the classification of the Green Deal as "*a zero-pollution ambition for a toxic-free environment*". There is a need to increase the use of modern mass spectrometric techniques for measurements of both radioactive and non-radioactive pollutants in monitoring labs and beyond. However, this will require increased access to certified reference materials traceable to the SI.

Objectives

The overall aim of the project is to bridge the gap between radiometric techniques and mass spectrometry for the characterisation and detection of polluting long-lived radionuclides and stable elements and element tracers by comparing and linking both techniques, thus significantly improving measurement uncertainties and detection limits.

The specific objectives of the project are:

1. To establish and compare the selectivity and detection limits of different types of mass spectrometers (e.g., AMS, HR-ICP-MS, ICP-MS/MS, ICP-QMS, MC-ICP-MS, SIMS, SNMS, TIMS) for selected radioactive pollutants (e.g., U, Np, Pu, Am) using isotope reference materials and/or activity standards. This includes

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: May 2024

assessing relative instrument performance with respect to current measurement challenges and establishing detection limits in relation to regulatory waste criteria levels or environmental regulations.

2. To develop measurement methods for isotope ratios that are traceable to the SI by using multi-collector ICP-MS and apply these methods on more commonly available techniques (ICP-MS/MS, ICP-QMS) by providing suitable operating procedures focussing on stable polluting elements (e.g., Li, B, Cr, Cd, Ni, Sb, Pb, U). To produce recommendations for sample processing, treatment, uncertainty budgets, and if feasible, the quantification of the so-called mass bias.
3. To develop two radioactive reference materials with the sample matrix containing radioactive pollutants (e.g., U, Np, Pu, Am) for use in an inter-laboratory comparison employing techniques used in objective 1, which will demonstrate the variations in parameters including detection limits, sample preparation requirements, sample introduction methods, total procedural time, and uncertainty budgets.
4. To implement and validate the methods for isotope ratio measurements established in objective 2 by the development of one aqueous certified reference material (CRM) that is certified for the same stable polluting elements with lowest possible uncertainties using multi-collector instruments, in order to facilitate the calibration of single collector ICP-MS, instrument validation, as well as quality control.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g., accredited laboratories), standards developing organisations and international organisations (JRC, CIPM CCs [CCQM-IRWG, CCQM-IAWG, CCRI], IAEA, ICRM) and end users (e.g., environmental monitoring agencies).

Progress beyond the state of the art and results

Measured selectivity and detection limits of different types of mass spectrometers for selected radioactive pollutants using single and mixed activity standard solutions

Non-radiometric techniques show great potential for the measurement of radioactive pollutants. However, the traceability and validation of the methods are missing. The project will go beyond the state of the art by establishing the capabilities of different mass spectrometry designs, such as:

- Accelerator Mass Spectrometry/Spectrometer (AMS),
- High Resolution Inductively Coupled Plasma Mass Spectrometry/Spectrometer (HR-ICP-MS),
- Inductively Coupled Plasma Tandem Mass Spectrometry/Spectrometer (ICP-MS/MS),
- Inductively Coupled Plasma Quadrupole Mass Spectrometry/Spectrometer (ICP-QMS),
- Multi-Collector Inductively Coupled Plasma Mass Spectrometry/Spectrometer (MC-ICP-MS),
- Secondary-Ion Mass Spectrometry/Spectrometer (SIMS),
- Secondary Neutral Mass Spectrometry/Spectrometer (SNMS) and
- Thermal Ionisation Mass Spectrometry/Spectrometer (TIMS).

This will be achieved by using single and mixed activity standard solutions of actinides (^{237}Np , $^{234,235,236,238}\text{U}$, $^{239,240}\text{Pu}$, ^{241}Am), accessible by mass spectrometry, at activities relevant to regulatory limits. The focus will be on relative instrument performance concerning current measurement challenges. It aims to establish detection limits at levels below current environmental regulations, reduce isobaric interferences, and compare decay counting techniques. The range of radionuclides chosen is well suited for comparison. This is based on the half-lives (<500 years to $>4 \times 10^9$ years), the presence of multiple spectral interferences that must be overcome to ensure accurate measurement, and the precise isotopic ratio measurements ($^{239}\text{Pu}/^{240}\text{Pu}$, $^{236}\text{U}/^{238}\text{U}$) for source identification.

The following progress and results have been achieved so far:

- The capabilities of participating laboratories with regards to the handling permission for the activities of radionuclides and limits of detection were established through a questionnaire. This set up the activity ranges that could be prepared, as well as information on the interferences, sample chemistry, sample preparation requirements, e.g., number of samples and sample volume for measurement.

- An extensive reporting template has been developed for the radionuclides of interest for the project that will also be of value for the new reference materials containing radioactive pollutants.
- A series of single and mixed radionuclide standard solutions have been prepared at very low activity levels for an inter-laboratory comparison exercise. The stable and radioactive impurity levels of these standards checked using a combination of decay counting and mass spectrometric techniques. Homogeneity and stability checks have been carried out and longer-term stability checks for the duration of the project are planned, given the low activity levels prepared and the absence of standard carrier added. The preparation of these standards was delayed by challenges in achieving sufficient purity levels in the starting materials and the required homogeneity for low activity samples.

SI-traceable measurement methods for isotope ratios of stable polluting elements

SI-traceable isotope ratios for Li, Pb, and U as pilot elements with relative measurement uncertainties (u_{rel} , of $<0.01\%$) will be realised. The process is based on the *ab initio* calibration for SI-traceable isotope ratios without any *a priori* assumptions, introduced for Mg as a three-isotope system in 2016. This approach will be expanded to other multi-isotope systems and will set the basis for the certification of the first iRM (e.g., Li) with SI-traceable isotope ratios and $u_{rel} \leq 0.01\%$. For many stable elements, enriched isotopes are not available, or the required uncertainty level does not justify the costs and efforts of applying a gravimetric isotope mixture approach to obtain SI-traceable isotope ratios. For quantitative elemental analysis, and for general isotope ratio applications, less expensive and laborious approaches based on inter-element normalisation will be developed.

The following progress and results have been achieved so far:

- For the selected single-element reference materials (Li, B, Cr, Cd, Ni, Sb, Pb, U) target isotope ratio values were determined.
- Participating laboratories performed the first evaluations of the different calibration approaches for isotope ratio measurements of the above elements (internal and/or external correction, mass bias regression model) in terms of accuracy and precision using reference materials selected in the project by different types of ICP-MS.
- The development of manual and automated separation techniques for the selected elements in the seawater matrix is underway.
- Data on isotope ratios of elements such as Li, B, Cr, Cd, Ni, Sb, Pb, and U obtained from different types of mass spectrometers such as ICP-MS, ICP-MS/MS, HR-ICP-MS, MC-ICP-MS, TIMS, and AMS are currently being collected. This data will be used to evaluate and model the instrumental mass fractionation for these elements.

Inter-laboratory comparison with two new reference materials containing radioactive pollutants

Existing radioactive Reference Materials (RM) and Certified Reference Materials (CRM) adapted to mass spectrometry measurements on environmental samples are limited and often lack relevant parameters, including isotopic ratios. The project will go beyond the state-of-the-art by developing two RMs – liquid and solid – containing the radioactive pollutants U, Np, Pu, Am for use in an inter-laboratory comparison. The project will employ techniques used for the measurement of the activity standards solutions. This will demonstrate the variations in parameters such as detection limits, sample preparation requirements, sample introduction methods, total procedural time, and uncertainty budgets. Eventually, this approach will help characterise the matrix related mass bias. Reference Materials, produced in this project, will be used in future QC measurements.

The following progress and results have been achieved so far:

- Two procedures of acid dissolution and fusion have been selected to completely decompose the materials and release radionuclides into solution.
- Two multi-steps procedures have been selected for the separation of U, Pu/Np and Am from the prepared solution, enabling the project to remove the sample matrix and interfering elements from these actinides.
- Three types of measurement techniques, alpha spectrometry, ICP-MS and AMS have been prepared for the measurement of the radionuclides of interest.

- A new procedure to synthesize a spikable solid reference material was developed. To lower activity uncertainty values, a hydrophobic silane precursor was used to limit the moisture uptake of the resulting material. The methodology is being used to prepare a 10 kg batch of inactive material. It will be distributed to perform blank measurements, to test the dissolution and separation procedures, and to study the matrix impact on mass spectrometry measurements.
- Seawater samples have been prepared, sterilized and sent to the laboratories for blank measurements. Some extra seawater samples were distributed for testing separation procedure in this complex matrix.

Aqueous certified reference material with stable polluting elements (and traces of radioactive pollutants) for the calibration of single-collector ICP-MS

One certified seawater reference material with clearly defined concentrations at natural levels will be developed for use in the validation of analytical procedures, supporting proficiency testing and quality control in future monitoring campaigns.

The following progress and results have been achieved so far:

- A total of 250 litres of seawater has been collected from the edge of the German Exclusive Economic Zone (North Sea) to serve as the basis for the development of two different reference materials in the project. The material has arrived at TÜBITAK and CMI laboratories.
- Based on the discussions at the M9 meeting on the cleaning of the bottles, all units were subjected to a cleaning procedure by washing with ultrapure acid followed by deionized water and drying in ISO 6 Clean Chemistry Laboratory.
- Processing of a candidate certified seawater reference material was completed in the ISO 6 Clean Chemistry Laboratory at TÜBITAK ÜME. Processing includes the following steps:
 1. The whole raw material (approximately 120 L) was transferred into a pre-cleaned HDPE Drum.
 2. The material underwent spiking by known quantities of Cd, Cr, Ni, Sb, and Pb.
 3. The material had been homogenized for four hours to ensure uniformity and consistency in its composition.
 4. The whole water was filtered from one drum to another using 0.8/0.2 µm filter after homogenization.
 5. Bottle filling was performed manually in the ISO 6 Clean Chemistry Laboratory.
 6. A total of 470 bottles were produced with each bottle containing 250 mL of processed material.
 7. The filled bottles were dispatched for gamma irradiation at 25 kGy.
 8. Gamma-irradiated units have been stored at +4°C, which is likely to maintain the stability of the material.
- Testing of long-term stability of the material (shelf life) at room temperature for 12 months was started in 08/2023 and will end in 08/2024. The measurements of all units for each analyte will be carried out simultaneously by the task distribution among the partners and will end in 11/2024.

Outcomes and impact

The following dissemination and communication activities have been undertaken so far:

- The project website is regularly updated with the latest information, such as the publishable summary, project flyer, project poster, newsletters etc.
- 18 presentations at conferences and workshops
- 5 presentations to national and international standards
- 3 internal training events
- 3 press releases

- Two issues of the project newsletter
- LinkedIn and Research Gate project pages created and updated regularly with the latest publishable summary, project flyer, project poster and newsletters.
- The project established a stakeholder committee of 24 members from 9 countries and 6 international organisations. It includes representatives from government funded bodies, pollution monitoring laboratories, instrument manufacturers and monitoring networks. This is mirrored by the larger stakeholder group of 50 stakeholders, which includes 6 additional countries and 23 organisations.

Outcomes for industrial and other user communities

This project will enable and harmonise measurement methods for the detection and characterisation, of both radioactive isotopes and stable polluting elements, in support of the EU Green Deal's aim toward a zero pollution, toxic-free environment. The measurement of the species in this project (Li, B, Cr, Ni, Cd, Sb, Pb, U, Np, Pu and Am) will benefit the users of such data, such as monitoring organisations and the owners of potentially polluting facilities. This project, by providing information to the ICP-MS (of whatever type) measurement community, will allow them to select the most appropriate technology (from AMS, HR-ICP-MS, ICP-MS/MS, ICP-QMS, MC-ICP-MS to single collector ICP-MS) to meet their needs. As a result, users seeking to invest in one of the available ICP-MS based modalities will be able to make informed decisions. The Europe-wide collaboration developed in the project will provide the foundation for future inter-laboratory comparison exercises for the determination of species of interest in a variety of environmental matrices where ICP-MS based techniques offer significant advantages over decay counting. The new RMs developed in this project will address the ongoing need to produce suitable and relevant (in terms of matrices and analytes) RMs that can validate state-of-the-art measurement capabilities.

Consortium members are active in raising awareness of the project at a variety of events where they are in attendance. To date, these have included 4 standards bodies, 8 international meetings/conferences, and 4 national meetings.

Three collaborators have signed a letter of agreement. The first collaborator is a company that offers special resins for highly specific chemical separations of various elements in the analysis of environmental matrices prior to measurements of individual isotopes. Together with the consortium members, the company intends to develop customised resins for elemental separations followed by mass spectrometry measurements. The second collaborator is a DI and the third collaborator is a national laboratory for Nuclear, Biological and Chemical Protection. Both collaborators contribute with their unique mass spectrometry measurement capabilities. Another seven industry partners are part of the stakeholder group, including the major producers of mass spectrometry systems.

Outcomes for the metrology and scientific communities

The scientific outcome of the proposed research will deliver validated and traceable analytical approaches for the analysis of the concentration of pollutants, as well as determining the source and monitoring any contamination of pollutants through isotope ratio measurements. This will close existing metrological gaps and will lead to a harmonisation of the different methods currently applied for the analysis of isotope ratios to support the investigation of natural environmental processes and anthropogenic impacts.

Combining the expertise in isotope ratio measurements of the Comité Consultatif pour la Quantité de Matière: métrologie en chimie et biologie (CCQM) and radioactivity measurement by the Comité Consultatif des Rayonnements Ionisants (CCRI) will provide new and innovative tools for advancing the application of mass spectrometry for contributing to improved half-life determinations.

The BIPM organised a targeted workshop from 14-16 February 2023, titled "CCRI-CCQM Workshop on the Use of Mass Spectrometry in Radionuclide Metrology: Opportunities and Challenges", attended by several members of the consortium (<https://www.bipm.org/en/committees/cc/ccri/wg/ccri-ccqm-ws/2023-02-14>). Several presentations were made by scientists working in the MetroPOEM-project, including an overview on the scope and goals of the project.

Additionally, BIPM has set up a new CCRI(II) Task Group on Mass spectrometry (CCRI(II)-MS- TG) (<https://www.bipm.org/en/committees/cc/ccri/wg/ccri-ii-ms-tg>) which includes three scientists from the MetroPOEM consortium. The CCRI (II) Task Group on Mass Spectrometry in Radionuclide Metrology has members from NPL, PTB and NIST. The ultimate aim is to establish the role of mass spectrometry as a metrological tool for radionuclide metrology. An early action of the group was to run a virtual workshop in early 2023 on the role of mass spectrometry for radionuclide metrology, with a follow-up workshop planned for the end of 2024. More recently, a survey was prepared that ran from November 2023 to January 2024 to establish the labs that are currently or have potential interest in mass spectrometry for radionuclide measurement, with 50 responses received from around the world.

The group meets monthly and sets out terms of reference that includes working with NMIs, DIs and analytical laboratories, working groups, consortia (including MetroPOEM) with current and planned programs in mass spectrometry. The group aims at preparing peer-reviewed publications on the current and future status of mass spectrometry for radionuclide metrology, as well as writing a report to the CCRI(II) on the task groups outcomes and proposing future activities to enhance CCRI(II)'s understanding in this field.

Outcomes for relevant standards

This project will deliver an improved system of metrology and will establish an infrastructure that directly supports the application of the following EU regulations or EU directives:

- Council Directive 2013/51/Euratom (22 October 2013): requirements for protecting the health of the general public concerning radioactive substances in water intended for human consumption.
- Council Directive 2013/59/Euratom (5 December 2013): basic safety standards for protection against the dangers arising from exposure to ionising radiation; Chapter VIII – Public Exposures.
- Treaty establishing the European Atomic Energy Community, Chapter III – Health Protection, Article 35: Each Member State shall set up the facilities necessary for the permanent control of the level of radioactivity in the atmosphere, water and soil and for controlling compliance with basic standards. The Commission shall have the right of access to such control facilities; it may examine their operation and efficiency.
- EU Regulation 995/2010: the origin of legal timber by, for example, determining the Sr isotope composition.
- EU Regulation 2729/2000, 2220/2004, 2030/2006, 555/2008 and 1169/2011: the provenance of food.
- Directive 2009/29/EC, decision No 406/2009/EC, directive 2009/31/EC: Climate research ($\delta^{11}\text{B}$), greenhouse gases (pathways of $\delta^{13}\text{C}$), carbon storage (possibly applicable for the geological assessment of Sr and Nd).

By implementing new traceability chains, different methods will be combined in the field of pollution monitoring, which will then lower the detection limits. This will result in better protection of the environment, provide new tools for complex studies in climate observation, support validated data collection of the European Research Centres and enhance the implementation of the ALARA goal expressed in the radiation protection regulation of the EC. Project consortium members are members of various standards committees and input to date is.

International:

- IUPAC Inorganic Chemistry Division
Assessment of absolute isotope ratios for the international isotope delta measurement standards, <https://iupac.org/project/2020-013-1-2000>
- IUPAC Commission on Isotopic Abundances and Atomic Weights
Terminology and definitions of quantities relating to isotopic analyses, <https://iupac.org/project/2023-014-2-200>
- CCQM IRWG
Terminology and definitions of quantities relating to isotopic analyses

- Committee participation: ISO TC 147 Water quality SC3 WG14 ICP-MS
ISO CET/TC 460/WG 6
FIRMS network
CCQM IAWG

National

- DIN (Germany) NA 062-08-15 AA
DIN 51013:2023-07 (Anorganische Isotopenanalytik - Begriffe und Verfahren)

Longer-term economic, social and environmental impacts

The integration of highly specialised MS techniques, such as Accelerator Mass Spectrometry/Spectrometer (AMS) and Secondary-Ion Mass Spectrometry/Spectrometer (SIMS), into the project, considerably widens the horizon for environmental monitoring or forensic studies and harmonises these detection methods with more commonly applied ICP-MS methods. The outcomes of the project will contribute to meeting the challenge of achieving highly sensitive and cost-effective pollution control. Using ICP-MS techniques in routine pollution monitoring allows the rapid determination of multiple elemental pollutants (both radioactive and stable) within a single sample. This ability, linked to the automated high sample throughput of ICP-MS systems, allows the capture of more and better sample information from single measurements. These factors will help to make a rapid and detailed mapping of pollutants, within defined areas, relatively straightforward. As a result, remediation strategies can be closely targeted and operated with good resolution. The cost of these activities will be reduced without losing effectiveness.

The development of validated and traceable methods will improve societal confidence in the measurement and quantification of pollutants across many sectors, such as manufacturing, industrial decommissioning and the long-term decommissioning and remediation of aged and disused nuclear sites. Accurate waste classification engenders public confidence and ensures inventories are correct for future infrastructure planning, such as the scale and design of pollutant remediation programmes.

The outputs from the project may be employed in several diverse fields including routine real-time monitoring, emergency response, geological dating and climate change studies through isotopic ratio measurements, and in other activities, such as nuclear forensics, decommissioning non-nuclear industries (such as the oil industry in the North Sea) and radiopharmaceutical facilities, where use is made of long-lived radioactive precursors. The collaboration between European laboratories established in this project is expected to continue beyond the end of the project.

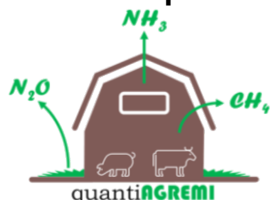
The stakeholder group consists of 14 national and international organisations with responsibilities in stable and radioactive pollution monitoring that are informed about the scope, goals and outcomes of the project.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
Coordinator: Dirk Arnold, PTB		Tel: +49 531 592 6100
Project website address: https://www.npl.co.uk/euramet/metropoem		E-mail: Dirk.Arnold@ptb.de
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	9. AU, Denmark	21. UNIVIE, Austria (joined May '24)
2. BAM, Germany	10. DTU, Denmark	
3. CEA, France	11. Hereon, Germany	
4. CMI, Czechia	12. HZDR, Germany	
5. JSI, Slovenia	13. IFE, Norway	
6. LNE, France	14. IFIN-HH, Romania	
7. STUK, Finland	15. LUH, Germany	
8. TÜBİTAK, Türkiye	16. MUL, Austria	
	17. NMBU, Norway	
	18. UH, Finland	
	19. VINS, Serbia	
	20. UGOT, Sweden (joined Jan '23)	
Associated Partners:		
22. ETHZ, Switzerland,		
23. LGC, United Kingdom ,		
24. NPL, United Kingdom		



Publishable Summary for 21GRD10 quantiAGREMI

On farm quantification of ammonia and greenhouse gas emissions from livestock production

Overview

Many current food production practices still result in air, water and soil pollution, contributing to biodiversity loss, climate change and poor air quality. Increasing global food demand drives ruminant livestock numbers, rapid land use change and nitrogen (N) fertiliser use, accelerating greenhouse gas (GHG) emissions. The aim of this research is to provide a SI-traceable field measurement infrastructure for accurate determination of animal houses emissions as well as nitrogen footprints. Mitigation measures can therefore be assessed to reduce emissions and improve inventories.

Need

The EU agricultural sector contributes to 93% of ammonia (NH_3) and 48% of methane (CH_4) emissions in Europe and dominates Europe's anthropogenic N_2O emissions (72%). While NH_3 is an important contributor to particulate matter, with adverse health effects estimated to cause 4.2 million premature deaths worldwide per year (2016), CH_4 and N_2O are potent GHG. The Farm to Fork strategy is a central part of the European Green Deal for a climate neutral Union in 2050. The strategy aims to reduce the GHG emissions from agriculture and food value chain to 55% compared to 1990 levels by 2030. Additionally, innovative CH_4 mitigation strategies are required to be explored under the "EU strategy to reduce CH_4 emissions". It is essential to develop a coordinated European metrology infrastructure to improve and reduce the uncertainty of emission data GHG and reactive N from agriculture, in order to understand the processes governing emissions, assess the efficiency and reliability of developed reduction strategies and to provide reliable evidence for policy makers who set emission targets. In addition, there is a requirement from the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Food and Agriculture Organisation (FAO) to reduce the environmental and climate footprint from agriculture.

Objectives

The overall objective of the project is to enable a more reliable quantification of livestock emissions and allow policy makers assessing and establishing efficient mitigations strategies.

The specific objectives of the project are:

1. To develop, building upon existing techniques, traceable techniques for quantifying NH_3 and CH_4 emissions from selected livestock housings with a target uncertainty of 10% (CH_4) and 20% (NH_3) for mechanically ventilated and 30% (CH_4) and 40% (NH_3) for naturally ventilated housing. In addition, to define target applications (e.g. animal category, housing systems) according to stakeholder needs.
2. To develop and characterise CO_2 , NH_3 and CH_4 emission monitoring techniques, considering atmospheric conditions, for enhanced spatial and temporal coverage.
3. To identify, using emissions data from objective 2, key-indicators (e.g. milk urea content and manure storage) and to improve emission models (e.g. based on feeding, climate conditions) for increasing the representativeness of the emission estimations and determine their uncertainty. In addition, to

Report Status:
PU – Public, fully open

Publishable Summary

Issued: March 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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develop farm-monitoring systems for evaluating the efficiency of reduction measures and provide management tools to farmers for ensuring reduction performance.

4. To reduce the uncertainty associated with up-scaling GHG emissions and nitrogen loss from soils by improving model parameterisation (e.g. relative contributions of nitrification and denitrification to N_2O emission) using field-deployable spectroscopic techniques to determine N_2O isotopic species for different production pathways. In addition, to improve methods for quantifying NH_3 deposition from livestock housing and tracing nitrogen isotopes (e.g. ^{15}N) in managed soils.
5. To facilitate the dissemination and uptake of the technology and measurement infrastructure developed in the project by (i) contributing to emissions inventory reports under the UNFCCC, (ii) providing guidelines to the measurement supply chain (researchers, commercial measuring institutes), expert groups (VERA, COST Action LivAGE) and standardisation developing organisations (CEN TC264) on techniques/modelling approaches to facilitate the establishment of decision matrices and the promotion of mitigation measures by policy makers, and (iii) providing farmers access to reliable methods for identifying efficient mitigation strategies and provide quantitative GHG emissions at farm level.

Progress beyond the state of the art and results

Development of techniques for the quantification of NH_3 and CH_4 emissions from selected livestock housings with a target uncertainty of 10% (CH_4) to 20% (NH_3) for mechanically ventilated and 30 % (CH_4) to 40 % (NH_3) for naturally ventilated housing and for target applications such as animal category and housing systems.

Objectives 1 will contribute to a more reliable quantification of GHG and NH_3 emissions from agriculture by improving existing and developing new measurement methods, characterising metrologically the emission measurements and providing complete uncertainty budgets. This will enable SI-traceable emission estimations. SI-traceable estimations and their uncertainty will contribute to the accuracy improvement of the inventories, thereby ensuring a better implementation check of the National Emission Ceilings Directive (NEC 2001/81/EC) and the UNECE 1999 Gothenburg Protocol (revised in 2012), which set national emission reduction commitments. For this purpose, the results of EMPIR JRP ENV55 MetNH3 will be used. That project aimed to achieve metrological traceability for ammonia measurements in ambient conditions by developing improved dried and wet reference gas mixtures (RGMs) by static and dynamic gravimetric generation methods of NH_3 amount fractions, as well as by developing laser-based optical transfer standards. The protocol for the intercomparison of wet and dry ammonia RGMs in the nmol/mol range in synthetic air has been developed and the planning has been defined. The campaign will be held from the end of April 2024 by sending the references to LNE. Laboratory work will be done until May 2024, with the final report planned for November 2024. The transfer from high-accuracy standards to field applicable methods was also established by employment of characterised exposure chambers and field sites for validation and comparison experiments.

Data on measurement ranges, conditions and required amount fractions have been collected. Estimation of ventilation rates is still pending. Linearity and repeatability of CH_4 and CO_2 measurements with a commercial CRDS analyser has been evaluated on data collected in an experimental dairy housing over several years (2015 – 2020). Also, linearity and repeatability of a commercial CRDS analyser for NH_3 has been tested in relevant concentration range using wet reference gas from the reference gas generator.

Target applications for emission measurement techniques for enhanced spatial and temporal coverage have been defined.

Development and characterisation of CO_2 , NH_3 and CH_4 emission monitoring techniques, considering atmospheric conditions, for enhanced spatial and temporal coverage.

Objective 2 will allow the development of new CO_2 , NH_3 and CH_4 emission monitoring techniques and their characterisation. The development of these new sensors is still on going. Three TRL 6 OEM modules have been developed and qualified in laboratory under ammonia exposure. Mobile measurements of a dairy farm were performed successfully. A more precise calibration set-up for this instrument is under development at VSL. Senseair K96 multi-gas NDIR sensor has been optimised and extensive lab characterisation has been performed. The K96 sensor has been integrated in a field deployable sensor system including data logging and wireless communication capabilities. Gasera has designed and manufactured the first prototype of a laser-based analyser for measuring CH_4 , NH_3 , N_2O and H_2O simultaneously with a single analyser unit. The spectral analysis is developed, and the system will be validated in co-operation with PTB.

The measurement protocols for laboratory testing of sensors have been developed and the collection of input from partners will start soon. It is shared with Objective 3.

Identification of key-indicators (e.g. milk urea content and manure storage) and improvement of emission models (e.g. based on feeding, climate conditions) for increasing the representativeness of the emission estimations and their uncertainty evaluation. Development of farm-monitoring systems for the evaluation of the reduction measures efficiency in order to provide management tools to farmers for ensuring reduction performance.

Objective 3 will allow step-by-step validation measurements in the laboratory and under real housing conditions to identify suitable sensors and to evaluate them with regard to their suitability and field of application (animal category, housing system, manure storage). There is now no clear solution for farmers and policy makers to measure GHG and reactive N emissions, and thus to develop a mitigation policy. This project will allow the sensors implementation, while a survey policy at the European scale will be developed.

NH₃ sensors has been tested in IMTelecom setup with the following protocol: NH₃ will be generated from cylinders into a 5 L chamber with a flow rate of 10 L/min, with the possibility to add water. LGR analyser is used as a reference. For calibration of the gas bench a Picarro is used as reference instead. Laboratory testing of CO₂ and CH₄ sensors will be held at LNE. The gas mixed from cylinders is diluted with clean pressurised air and fed into a T- and RH-controlled climate chamber.

The conditions for intercomparisons allowing to tests the instruments on the fields will be fixed during the second half of the project.

Reduction of the uncertainty associated with up-scaling GHG emissions and nitrogen loss from soils, by improving model parameterisation (e.g. relative contributions of nitrification and denitrification to N₂O emission) and with the use of field-deployable spectroscopic techniques for defining the N₂O isotopic species for different production pathways. Improvement of methods for NH₃ deposition quantification from livestock housing and tracing nitrogen isotopes (e.g. ¹⁵N) in managed soils.

Objective 4 will reduce the uncertainty of N₂O inventories from agricultural soils and improve the quantification of NH₃ footprint around livestock buildings through i) evaluating the methodologies used to study the fate of NH₃ released from animal housings and ii) the study of the capability of current field N₂O emission measurements to attribute N₂O emitted from soils to the different microbial N production processes. N₂O emissions from soils have constant emission factors applied, irrespective of soil properties and meteorology, which leads to large uncertainties. In addition, human activities profoundly influence the N-cycle by converting more N into reactive N forms than all of Earth's terrestrial processes combined. Thereby, nitrogen cycles exceed their safe operating space in Europe, by a factor of 3.3 resulting in diffuse N pollution of terrestrial and aquatic ecosystems. The results will be used to determine bias and reduce uncertainty arising from near-field N deposition and parametrisation of different N₂O production processes in biogeochemical models.

The design of N release experiment focused on the identification of the most suitable experimental site for the release experiment. The grassland site Graswang of the TERENO pre-Alpine Observatory was identified as the most suitable site. Also, NH₃ release experiment was carried out in the period June 14th to July 17th 2023. Different techniques including open- and closed-path analysers in eddy-covariance, aerodynamic gradient method, and chamber setups were applied for an inter-comparison of concentration and flux measurements.

Calibration and correction strategy is ongoing and expected to be finalised in December 23rd. Analyser validation work was initiated and is ongoing. A draft software algorithm for data correction was established and will be finalised with correction factors. The intercomparison is shared with Objective 2 and it is in preparation.

Outcomes and impact

The project successfully presented the project objectives at the International Metrology Congress (CIM 2023) and the consortium secured the participation of 19 Stakeholders representing a good range of features such as public bodies, large Industrial enterprises, and research organisations. M9 meeting has been held on the 7th of November 2023. The project is on track and all the due tasks have been delivered on time. It has been followed with the first stakeholder meeting, in which the consortium presented the context of the project and the deliverables to the stakeholders. A special session dedicated to the project results has been organised in conjunction with the Air Quality 2024 Conference in Helsinki, which has been held in May 2024. 7 presentations on the project results have been given for this special session.

The project results will create impact by providing policy-makers with the tools required to develop efficient mitigation measures for emissions. Improved SI-traceable estimations of NH₃ and GHG emissions from agriculture, with a defined uncertainty available will create further impact not only on the scientific community, by enhancing emission data comparability across monitoring studies, but also support national agencies, by improving emission inventories for air pollutants and greenhouse gases

Outcomes for industrial and other user communities

Research outputs, such as improved accuracy of emissions, enhanced spatial and temporal measurements, and reduced model input uncertainties, will be beneficial to farmers, industry, agricultural agencies and national authorities. It will allow users to evaluate, with a higher level of confidence, the measures proposed for reducing emissions (e.g. set of measures for reducing NH₃ included in Directive 2016/2284/EU) and therefore to select and implement the strategies with the highest effectiveness, whilst considering the benefit-to-cost ratio. The impact of this work will reach beyond Europe as the work and the results will be communicated to international agencies such as the WMO and the FAO on how to reduce the environmental and climate footprint of the food system and lead to a global transition towards competitive sustainability from farm to fork.

Outcomes for the metrology and scientific communities

The project aims to characterise metrologically state-of-the-art techniques for estimating emissions from livestock (objective 1), such as natural and artificial tracer gas methods. This characterisation, along with the resulting method comparison, will create impact on the scientific community by offering tools to perform accurate decision matrix analysis of appropriate techniques and/or potential reference. Furthermore, the validation of measurement techniques to estimate the N footprint surrounding livestock buildings including NH₃ deposition, N₂O soil emission fluxes and isotope signatures, will generate data that will improve process descriptions and reduce biogeochemical model uncertainties. These will result in methodologies which will provide a better understanding on nitrogen conversions and fluxes between compartments. Furthermore, this project will enable a European fit-for-purpose metrological infrastructure (partly developed during the EMRP projects ENV55 MetNH₃, ENV52 HIGHGAS, IND63 MetAMC and the EMPIR project 16ENV06 SIRS) for direct field applications, and in particular for trace level gases of NH₃ and GHG. It will also enhance the collaboration between different fields/laboratories thus fostering cross-disciplinary tasks and applications (e.g. gas measurement, wind measurement, modelling approach).

Outcomes for relevant standards

This project supports international standardisation technical committees and directive such as CEN/TC264/WG11 and *ad hoc group Stationary Source Emissions — Methods for the Quantification of Diffuse Emissions*, ISO/TC146 (*air quality – ambient air and emissions from stationary sources*) and the Directive 2008/50/EC for air quality. The consortium will disseminate its findings through new or revised guidelines and recommendations with their active participation in several working groups (e.g. CEN/TC264/WG12, ISO/TC158, new WMO-GAW measurement guidelines). Furthermore, the work will especially support the Directive 2008/50/EC for air quality as well as regulation (EC) No 842/2006 by increasing the confidence in the emission/immission measurements and by enabling improved evaluation tools for implemented emission reduction measures.

Longer-term economic, social and environmental impacts

Effective measures and strategies will in turn result in lower socio-economic costs associated with environmental and health issues. For example, avoiding premature deaths associated with NH₃ emissions will translate into benefits > 14800 M€/year in Europe. In the case of measures for reducing NH₃ emissions, the estimated implementation costs range between 80 and 3780 M€. In particular, the project will have a direct impact on the work carried out by expert groups such as VERA (Verification of Environmental Technologies for Agricultural Production), GRA (Global Research Alliance) and the COST LivAGE Action (European Cooperation in Science and Technology - Ammonia and Greenhouse Gases Emissions from Animal Production Buildings). The outputs will facilitate their tasks on harmonisation of measurements and modelling aspects to reduce emissions from livestock buildings, which will additionally support the strategy adopted under the "EU Methane Strategy" and "Farm-to-Fork" as part of the European Green Deal.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 November 2022, 36months
Coordinator: PaolaFiscaro, LNE Tel: +33 140433759 E-mail: paola.fiscaro@lne.fr Project website address: https://www.lgcgroup.com/our-programmes/metpart-quantiagremi/		
Internal Beneficiaries: 1. LNE, France 2. CMI, Czechia 3. PTB, Germany 4. TUBITAK, Türkiye 5. VSL, Netherlands 6. VTT, Finland	External Beneficiaries: 7. GASERA, Finland 8. IMTelecom, France 9. INRAE, France 10. KIT, Germany 11. LUKE, Finland 12. Senseair, Sweden 13. TI, Germany 14. TNO, Netherlands 15. WR, Netherlands	Unfunded Beneficiaries: 16. Vaisala, Finland
Associated Partners: 17. Empa, Switzerland, 18. LGC, United Kingdom, 19. METAS, Switzerland, 20. UKCEH, United Kingdom, 21. WBF-Agroscope, Switzerland		

Publishable Summary for 21NRM01 HiDyn

Support for the standardisation of luminance distribution measurements for assessing glare and obtrusive light using high-dynamic-range imaging systems

Overview

Luminance distribution measurements with high dynamic range (HDR) are required for various applications (e.g. measurement of new LED- or laser-based car headlights, obtrusive light and glare evaluation of indoor and outdoor scenes) where high contrast levels exist simultaneously in one image. Imaging luminance measurement devices (ILMD) and red-green-blue (RGB)-based cameras are often used for such assessments. HDR measurements are then achieved by post-processing image sequences, but standardisation and uncertainty statements are usually absent, which makes it impossible to fully explore the potential and limits of these systems. This project aims to develop procedures for using HDR imaging measurement systems in luminance distribution measurements and glare assessment, standardise the determination of the instrument performance, including associated uncertainties, and select an HDR algorithm adequate for SI-traceable measurements. This is expected to support relevant legislations on glare and obtrusive light mitigation with traceable and trustable field based HDR luminance measurements, contribute to a proper assessment of lighting installations regarding safety and discomfort from glare and obtrusive light sources, and increase working place ergonomics as well as safety levels in roads suffering from glare from lighting installations and environmental impact of obtrusive light.

Need

The complexity of the human visual system allows adaptation to extremely dark and bright lighting conditions. Due to its very large dynamic range for lightness perception (11 orders of magnitude of luminance), humans can safely and comfortably navigate the world, and perform tasks involving vision in lighting environments with very high luminance contrast. However, some lighting environments can be disturbing for some tasks and may pose issues regarding safety. Therefore, it is necessary to study these environments and adapt them to more adequate lighting. In particular, unsuitable distribution or extreme luminance contrast can produce glare, a vision condition in which there is discomfort or a reduction in the ability to see details or objects, and spill light with certain attributes, which can be obtrusive and give rise to annoyance, discomfort, distraction or a reduction in ability to see essential information such as a traffic signal. The evaluation of glare or obtrusive light, and other visual aspects important for safety and comfort, rely on experiments presenting a high luminance contrast. The characterisation of such scenes requires measuring instruments specifically designed for these conditions. In the recent years, an increasing number of research fields and industry applications have been using HDR imaging technologies. However, there is currently no metrological certainty obtained with measurements performed using commercial HDR imaging measurement systems, and glare and obtrusive light evaluations using such systems are not SI-traceable, which can lead to major shortcomings in safety and comfort for many visual activities. Additionally, as expressed in the 2019 revision of the EU's Green Public Procurement Criteria for Road Lighting and Traffic Signals, obtrusive light is an important issue for wildlife (high insect mortality, disruption of the migration of birds) and human quality of life (sleep pattern disruption), as well as for astronomical observations.

CIE recognised the need for further work on this field and submitted two documents to EURAMET identifying a lack of traceable SI calibration, poor long-term stability, and inadequate relative spectral responsivity, as well as the need for the calibration and characterisation of HDR-cameras used for luminance distribution measurements.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: July 2024

The measurement of luminance distribution covers such a broad range of topics, that the diversity of stakeholders' sectors requiring reliable guidance for traceable HDR imaging luminance measurements is immense (e.g. CIE, CEN, national metrological institutes (NMIs), designated institutes (DIs), ILMD manufacturers, scientific community, end-users of HDR imaging systems dealing with quantitative glare and obtrusive light evaluation and all the communities impacted by obtrusive light, glare and high-contrast luminance scenes).

It is necessary to make references available to characterise HDR imaging measurement systems, and to establish instruments' requirements to guarantee traceable HDR luminance measurements as well as to demonstrate the comparability of the results. The latter includes the characterisation of the stray light produced inside the camera. It is necessary to improve the estimation of the uncertainty by the proper evaluation of these sources of error and related examples are beneficial to ensure competence of operators of such measurement devices. Existing HDR algorithms must be evaluated from a metrological point of view, in order to provide a recommendation, if not of a single HDR algorithm, at least of the requirements they need to fulfil for traceable luminance measurements and assessments of glare and obtrusive light. Finally, guidelines on the determination of uncertainty budgets for HDR luminance imaging measurements, as well as glare evaluation, are required to support European stakeholders and feed the work of standardisation bodies (e.g., CIE and CEN).

Objectives

The overall goal of this project is to enable the traceability and characterisation of HDR imaging luminance systems, and to support the standardisation of luminance distribution measurement methods, which are required for glare, light pollution, and other lighting assessments. This will involve developing HDR luminance standards required for the characterisation of HDR imaging measurement systems and developing metrics and guidelines for the determination of the associated uncertainties.

The specific objectives of the project are:

1. To develop luminance reference standards (i.e. sources) with high dynamic contrast pattern (covering at least 6 orders of magnitude) in order to characterise the dynamic range and spectral mismatch for different types of commercial instruments that are available for luminance distribution measurements (e.g. ILMD, RGB matrix sensor cameras). This should be based on the recommendations stated in CIE 232:2019 and CIE 244:2021 and allow the reliable assessment of glare and obtrusive light.
2. To model and verify HDR luminance measurements (including non-linearity, internal stray-light, and lens flare), with the objective of reproducibly determining the input data required for the models (average luminance, luminous surfaces, if required contrasts in the glare source, peripheral angle). To define the requirements for traceable instrumentation and to demonstrate the inter-comparability of HDR luminance measurements (in general and between different camera technologies), including the effect of its uncertainty on glare assessment.
3. To develop an algorithm for (i) generating an HDR-luminance image from a sequence of multiple raw images and (ii) enabling traceability of relative images scaled to one or a few traceable spot measurements of the scene.
4. To develop guidance on the determination of uncertainty budgets for HDR luminance imaging measurements of single pixels and integral values (e.g. evaluation region, illuminance) as well as glare evaluation, according to existing standards EN 17037:2019 [2], EN 13201-2:2015 [3] and EN 12464 1:2011 [4]. This should include a report on the relevance of existing quality indices and test methods regarding HDR imaging luminance systems.
5. To contribute to the standards development work of CIE TC 2-86, CIE TC 2-95, CIE TC 3-57, CIE TC 4 58, TC 8-18, CEN TC 169, and the resumption and continuation of the work of CIE TC 2 59 and CIE TC 4-33 (both inactive), to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who will use them (e.g. manufacturers of RGB sensors and cameras), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

This project builds on and will progress beyond different projects.

In the EMPIR project 19NRM02 RevStdLED, the traceability of luminance imaging measurement devices has been addressed by a training and a published good practice guide "[for setting up an uncertainty budget for the measurement of luminance distributions including correlation of the 2D datasets](#)". The general model of evaluation and uncertainty budget for luminance measurements is picked up in this project as a foundation. However, RevStdLED aimed to reduce its complexity for selected individual applications relevant to test laboratories, and namely does not consider RGB matrix cameras nor HDR imaging systems for which the uncertainty contributions will have different significances. In this project, 21NRM01 HiDyn, both are considered and will be used to complement the good practice guide of RevStdLED with a supplement.

In the EMPIR project 18SIB03 BxDiff, HDR imaging systems had been used for studying the relation of reflectance measurements at different scales, on texturised, structured and translucent materials. However, BxDiff did not address the standardisation of an HDR algorithm nor the development of a reference source with luminance contrast. Both will be implemented by this project by also considering the experience from the studies and evaluating measurement data already at hand by partners from the consortium.

In the EMPIR project 20NRM01 MetTLM, the research regarding imaging devices focusses on spatial resolved temporal light modulation (TLM) measurement modes of luminaires and extended scenes, and vivid examples demonstrating its feasibility using ILMDs and RGB matrix cameras. In this context, high contrast luminance scenes or sources had been included in the targeted measurements. This project benefits from the experience gained in MetTLM and collaborates on the HDR measurement of TLM sources also by demonstration for errors of imaging luminance measurements caused by TLM and by giving guidance how to avoid them. This development of guidance about HDR imaging luminance measurements of field scenes presenting TLM will be included in the good practice guide of this project, 21NRM01 HiDyn, and thereby extend the state of the art.

Objective 1: High contrast reference luminance standard source of at least 6 orders of magnitude

In this project, a type of high contrast reference standard source of at least 6 orders of magnitude is developed, simultaneously presenting luminance levels about 0.1 cd/m^2 to about 100 kcd/m^2 or more, and a light trap of $<0.01 \text{ cd/m}^2$.

The requirements for the reference source were agreed within the consortium. An internal report has been written, although it is still subject to revision. Existing experimental or commercial technologies suitable to be used for the development of the reference standard sources were examined and their different properties collected in a specification matrix. A commercial LED-based light source that includes a light mixing chamber was selected as the basis for the reference luminance source. A modular light source including straylight reduction and optional neutral density filters as a configuration parameter has already been developed. These prototypes realise luminance values from around 0.5 cd/m^2 to 160 kcd/m^2 , which can be varied in steps by setting the hardware configuration and in addition within about half an order of magnitude by tuning the electrical operation condition. A measurement of a test scene based on two of these prototypes of the reference source and a light trap has been carried out using three ILMDs, showing above 5,8 decades of contrast in the luminance images, but the intermediate luminance's are significantly affected by straylight from other sources inside the scene. After revising the initial design regarding this, seven artefacts (light sources) providing luminance values from around 0.1 cd/m^2 to 100 kcd/m^2 were manufactured and photometrically characterised.

The luminance of the sources will be determined with an expanded uncertainty no larger than 1 % for the brightest source and no larger than 2 % for the dimmest one. This type of standard source will cover the needs for testing and characterisation of measurement systems with narrow and wide measurement fields via a modular design concept. It will be designed and developed to meet the requirements of luminance dynamic range for applications and measurement needs of the relevant standards and documents, like CIE 232:2019, CIE 150:2017, and CIE TN 014:2023.

Objective 2: Validation of HDR luminance measurements

Characterisation procedures using the reference luminance standard source and beyond will be developed. They will allow the validation of the assessment of glare and obtrusive light, and the metrological demonstration of the comparability of evaluations by different HDR imaging technologies. At least three types of HDR imaging

measurement systems will be tested (ILMD, commercial DSLR, camera based on an RGB matrix sensor). The comparability of measurements by these device types will be investigated through laboratory and field tests using the characterised systems.

Objective 3: Harmonised HDR algorithm for traceable HDR luminance measurements

This project will go beyond the state of the art by developing a dedicated HDR algorithm which will include functionalities that are missing from existing algorithms (e.g. estimating the uncertainty by considering also contributions from external standards which are beyond intrinsic information, like pixel signal noise, and by minimising uncertainty based on such traceable information) and will serve the metrological needs of HDR imaging measurements, including the propagation of uncertainties. It will be implemented in source code that will be distributed under an open-source license. Relevant HDR algorithms were preselected from the literature and implemented in code (MATLAB). A methodology for evaluating HDR algorithms was developed and tested for identifying HDR algorithms that are able to perform well for traceable luminance measurements. The proposed methodology is being adopted by the involved partners and will be improved in the future if necessary. This had been presented at the 30th Quadrennial Session of the CIE in Ljubljana (September 2023). On the other hand, an analytical study on the impact of the signal-to-noise ratio on the performance of the preselected HDR algorithms was presented during the first progress meeting held in Prague.

Objective 4: Uncertainty estimation of HDR luminance measurements, propagation to glare and obtrusive light assessment, and relevance of existing quality indices

This project will develop a model and a good practice guide for the uncertainty propagation of luminance measurements and of glare and obtrusive light evaluation using HDR imaging systems. It will be developed using data from the characterisation of the investigated HDR imaging technologies and demonstrated with the newly developed reference standard source, and field measurements. The part of the model regarding the uncertainty propagation in glare and obtrusive light assessment will be validated using dedicated measurements in well documented lighting installations. The model will be directly implemented with the algorithm developed for HDR processing.

A measurement model has been proposed in an internal report, where the different parameters relevant for errors and thus uncertainties in HDR imaging luminance measurements are described in detail. Details of this model are under discussion considering also findings from preceding work about estimating uncertainty contributions, i.e. the ILDM configuration checklist and training material from the EMPIR JRP 19NRM01 RevStdLED.

The identification of the relevant parameters that should be taken into account in the uncertainty analysis of glare evaluation has been considered. The key components of glare metrics have been identified in the relevant standards and technical reports. An internal report was created which will be used for ongoing activities in the uncertainty evaluation on the measurement of glare and obtrusive light.

Outcomes and impact

Attached to the CIE annual meeting 2022 in Athens, Greece, a stakeholder meeting was held in which this consortium, its objectives, planned implementation, and deliverables were introduced and the needs as well as important aspects of this project were discussed. An updated status of the project and results was reported to stakeholders in an oral presentation by the coordinator in the annual meeting of the Euramet TC-PR in January 2024. The project's stakeholder committee currently includes 21 institutions (standardization bodies, organizations, national metrology institutes, universities, companies) that have declared interest in the projects results. In the first eighteen months of the project representatives of the consortium gave 3 presentations in scientific conferences and have attended and contributed to several meetings of ten relevant national and international standardisation Technical Committees, including the CIE TC 2-86 "Glare Measurement by Imaging Luminance Measurement Device (ILMD)" in which meeting on 25th of May 2023 the evaluation of HDR algorithms performed by the project were presented.

In an onboarding meeting for newly hired employees, who have joined the consortium after the kick-off meeting, an overview of the projects technical aspects was provided, which the newcomers agreed was very useful. During a one-day internal consortium training event held at CMI, Prague, a practical introduction to the developed reference source prototype and its measurements using a spot luminance meter and ILMDs was given as a tutorial. This clarified details regarding handling and operation of the developed reference source and also covered setting up a scene with HDR luminance contrast and performing measurements using the prototypes. In addition, sessions on lab-based measurements dedicated to the characterization of ILMDs and

industrial vision cameras using the seven revised luminance sources for colleagues from three participants using various arrangement of sources and ILMD configurations (lenses, aperture) had been held in March 2024 at CMI, Prague. An outdoor measurement session was held at the LED catwalk of TUB, Berlin, (a street installation for research) during the M18 full consortium meeting in March 2024 using three of the revised luminance sources, light traps, and measurement devices from six partners.

Outcomes for industrial and other user communities

HDR imaging measurement systems have been used in industry for more than 30 years for production monitoring and for the generation of ray data from luminance images. Due to the missing traceability, they were only used to analyse relative changes between consecutive HDR measurements made under the same conditions. Traceability would make HDR measurements from different measurement systems and varying conditions comparable. Different end-users e.g. manufacturers of luminaires and ILMD manufacturers would benefit from this traceability by a more flexible application of HDR measurement systems. Authorities currently do not assess photometric glare neither from road lights nor from workplace lighting during daylight nor from façade shading systems, although citizens often complain about inappropriate installations which produce discomfort to pedestrians and disturbing glare within properties and dwellings. On-site glare and obtrusive light evaluation cannot be accomplished by relative measurement and without standard procedures and affordable measurement devices. With the results of the project, it will be possible for the first time to ensure the reproducibility and comparability of these kind of measurements, even for non-standardised measurement geometries on site. To promote the uptake of the project outputs, the consortium will organise workshops for industrial stakeholders and end-users and promote these online, at standardisation meetings and via the stakeholder committee.

Outcomes for the metrology and scientific communities

This project will provide tools, in the form of guidelines, open design guides and open-source software, which are all necessary for the realisation of traceable measurements and for a proper assessment of uncertainty in the process of capturing, processing and combining a sequence of low dynamic range (LDR) images to an HDR luminance image, and of assessing glare and obtrusive light. These results will help NMIs to offer new characterisation services for HDR imaging luminance measurement systems and to develop activities for in-situ measurements of scenes requiring a glare or obtrusive light evaluation.

The project will also, for the first time, provide a metrological basis for scientific results to be comparable and reliable, in the field of glare assessment, where there is a lack of metrological considerations. Thanks to the procedures and recommendations developed for measuring high luminance contrasts, scientists will have the tools to improve device characterisation and to validate the traceability of their measurements. To support the adoption of these new tools, this project will provide hands-on training in the correct handling of HDR imaging luminance meters. To promote the uptake of the project outputs, the consortium will organise a workshop for the research community and promote this online, at standardisation meetings and via the stakeholder committee.

So far two proceeding papers related to scientific presentations given by members of the consortium in the CIE Quadrennial Session 2023 conference had been published as open access literature:

- Schrader, C., Ledig, J. "SPECTRAL DEPENDENT NON-LINEARITY OF CHARGE ACCUMULATING PIXEL MATRIX SENSORS", Proceedings of the 30th CIE SESSION", CIE 2023, [doi:10.25039/x50.2023.OP077](https://doi.org/10.25039/x50.2023.OP077)
- Sáez, Á., Ferrero, A., Ledig, J., Schrader, C., Gevaux, L., Dupiau, A., Maltezos, E., Antonopoulos, M., Rezazadeh, Y., Bouroussis, C., "FRAMEWORK FOR EVALUATION OF PROCEDURES FOR HDR LUMINANCE IMAGING MEASUREMENTS", Proceedings of the 30th CIE SESSION", CIE 2023, [doi:10.25039/x50.2023.PO033](https://doi.org/10.25039/x50.2023.PO033)

Outcomes for relevant standards

This project provides input to upcoming standardisation. This is achieved by participation and contribution to several technical committees of the CIE (e.g. CIE TC 2-62, TC 2-86, TC 2-95, TC 8-18, JTC 12). This will indirectly influence standards developed by other standardisation bodies, such as the International Organization for Standardization (ISO), the Comité Européen de Normalisation (CEN) and the International Electrotechnical Commission (IEC). The results of this normative research project will provide the necessary

conditions for the application of the latest CIE reports e.g. CIE 244:2021 and CIE TN 014:2023. Research on glare and human vision strongly depends on the setup and characterisation of test scenes with extremely high and very low luminance levels at the same time. These scenes can only be measured and quantified via imaging systems that offer HDR functionality, yet not standardised nor metrologically validated. The known deviations are too large at the moment and critically not covered by corresponding uncertainty contributions. Only a correct classification and limit definition of different camera systems based on an associated uncertainty assessment will close this serious gap. With the results of the project, it will be possible to reproducibly test the existing glare assessment models for the first time, and make recommendations for their application. This is an elementary step towards effectively combating discomfort glare. Several current TCs of CIE will benefit from the results of this project, in particular those related to the work involving applications of ILMDs. For this reason, CIE was selected as the Chief Stakeholder. In addition, new TCs are expected to be proposed to exploit the scientific results of this project. To promote the uptake of the project outputs by the standardisation community, the consortium will organise an outdoor measurement session for selected stakeholders in Berlin in March 2025 and a dedicated CIE workshop under the CIE Midterm Meeting & Conference in 2025.

Longer-term economic, social and environmental impacts

Light pollution, obtrusive light and light emission are currently gaining enormous societal and political importance. The massive replacement of traditional lamps by LED-based light sources with much higher luminous efficacy often encounters rebound effects and, in the scope of obtrusive light, even backfires due to the enormous luminance of these new light sources. The massive insect mortality, the constantly increasing number of people suffering from low sleep quality, the climate protection-driven necessity to use light only where it is really needed - and to use high luminance points in connection with this - make a clear photometric characterisation of the outdoor lighting installations regarding their obtrusiveness and glare indispensable. However, this will only be possible when a measurement technology exists for such situations to be evaluated on site. Traditional spot luminance meters are completely unsuitable for today's LED luminaires to fulfil this task since they cannot sample the complex angular distribution, plurality, and the temporal and spatial character of the outdoor light scenes. The uptake of the results of this project will enable for the first time a metrologically-based field assessment of glare, which in the longer term will make possible to mitigate the future risks of inadequate evaluations of glare and obtrusive situations, and therefore will have a major impact mainly on public safety but also concerning environmental protection, biodiversity and visual comfort.

List of publications

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 October 2022, 36 months	
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Chief Stakeholder Organisation: International Commission on Illumination (CIE)		Chief Stakeholder Contact: Diana Wernisch	
Internal Beneficiaries: 1. PTB, Germany 2. Aalto, Finland 3. CMI, Czechia 4. CNAM, France 5. CSIC, Spain	External Beneficiaries: 6. ICCS, Greece 7. TUB, Germany	Unfunded Beneficiaries:	
Associated Partners: 8. EPFL, Switzerland 9. METAS, Switzerland			

Publishable Summary for 21NRM02 Digital-IT Metrology for digital substation instrumentation

Overview

Due to the wider use of decentralised renewable energy resources, future electrical power grids require real-time control and monitoring to ensure their stability under more challenging conditions. Digital substation solutions according to IEC 61850 and IEC 61869 are increasingly replacing analogue instrumentation which are approaching the end of their useful lifespan. To support the European electrical power industry, this project will provide the currently missing solutions for the calibration and timing of new types of digital substation instrumentation, e.g. sampled value (SV) enabled equipment such as stand-alone merging units (SAMUs), digital instrument transformers and instrument transformer measuring bridges. The project will also support IEC TC 38 'Instrument Transformers' in their work on the revision of the related standards, with the goal of proposing solutions for more precise measurements of digital substation instrumentation.

Need

The decarbonisation of energy systems has resulted in significant changes in electrical power grids, due to the wide-scale connection of decentralised renewable energy resources. Future electrical power grids need real-time capable control and monitoring systems to ensure stability under increasingly complex conditions, as well as metering systems, to ensure fair trading of electrical energy.

New standards in the IEC 61869 series (on instrument transformers) have helped to address the digital communication of new electronic instrument transformers, as well as SAMUs (which are digitisers for analogue instrument transformers). The IEC 61850 standard series (on communication protocols for intelligent electronic devices at electrical substations) is also under revision and adding new definitions for routable SV data in order to establish a truly real time wide area measurement system. These new standards have helped to boost the transition from traditional analogue instrumentation towards new digital substation instrumentation technology, both on transmission and on distribution level. However, to be able to fully support this change, standardisation bodies need to further develop their standards to include the metrological aspects of digital substation instrumentation.

Currently, there is a lack of calibration methods and metrological infrastructure for new digital substation instrumentation e.g. SV enabled equipment. Therefore, new metrology-level facilities are needed to be able to test and to validate the performance of such intelligent electronic devices (IEDs). Further to this, solutions for higher sampling rates and PTP timing required by the new standards (for digital substation instrumentation) need to be developed.

The importance of this topic and its needs have been highlighted in the European Network of Transmission System Operators for Electricity's (ENTSO-E) new "*Research, Development & Innovation Roadmap 2020 – 2030*", where digitalisation is one of the four structural trends identified as affecting the European power system of which '*digitally-enabled substations of the future*' are a critical part. In addition, IEC TC 38 has recognised digital substations as one of the emerging trends related standardisation in their Strategic Business Plan. Finally, EURAMET's European Metrology Network for Smart Electricity Grids (EMN SEG) has identified digital substations as one of the key priorities in their strategic research agenda.

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: April 2024

Objectives

The overall goal of this project is to develop the metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation (i.e. SV enabled equipment such as SAMUs, digital instrument transformers and instrument transformer measuring bridges).

The specific objectives of the project are:

1. To **develop and calibrate reference systems (hardware) for calibration of SV enabled equipment**, covering the new requirements of recently released IEC standards. To develop new hardware for traceable measurement of new data rates up to 96000 samples per second (SPS), for the related measurement bandwidth up to c. 40 kHz.
2. To **develop software for controlling the setups and handling of SV data streams** and develop new data processing and uncertainty estimation approaches for new data rates up to 96000 SPS.
3. To **develop communication and timing networks**, in participating laboratories, by creating ethernet networks that will transmit SV data and Precision Time Protocol (PTP)-based timing between commercial devices. To **establish a traceable link between PTP timing and 1PPS (One Pulse Per Second) reference pulse** with a target uncertainty of 100 ns.
4. To provide the data, methods, guidelines and recommendations, which are necessary for the calibration of SV enabled equipment, to IEC TC 38. To integrate the plans for future research activities on the European Metrology Network for Smart Electricity Grids (EMN SEG).
5. To contribute to the standards development work of the technical committee IEC TC 38. Outputs will be in a form that can be incorporated into future standards at the earliest opportunity and will be communicated through a variety of media to the standards community and to end users (equipment manufacturers, transmission system operators (TSO), distribution system operators (DSO), and customers).

Progress beyond the state of the art and results

Primary reference systems for calibration of SV enabled equipment

Steps towards developing the capability to calibrate SV enabled equipment were taken in the preceding 17IND06 FutureGrid II project. Basic calibrations of SV based equipment are now possible by some National Metrology Institutes (NMIs) using their SAMUs, however they are only for basic measurements like Root Mean Square (RMS) voltage and RMS current. In addition, traceable measurement services are limited mainly to low sampling rates (4 kSPS) using the 1PPS timing protocol.

This project will extend traceable calibration services to both higher sampling rates (14.4 kSPS and 96 kSPS) and to equipment working on the PTP timing protocol, as required by the new standards. Calibration services will also be developed and implemented at metrology beneficiaries that have so far been unable to calibrate digital instrument transformers or SAMUs.

A literature review on requirements for reference SAMUs has been performed.

The modification and extension of the capabilities of an existing reference SAMU calibrator in four alternative ways that vary in the amplitude of the input signals, phases available, bandwidth, and accuracy are under investigation. Tests defining the accuracy on the alternative setups of the modified calibrator are ongoing.

The 96 kHz sample rate has been implemented in the reference SAMU from 17IND06 FutureGrid II.

The SAMU calibrator has been modified to incorporate a higher sampling rate for the calibration of signals with components from 1 kHz up to 40 kHz. The setup is single-phase. Work on the setup for calibration in the frequency range between 50 Hz and 1 kHz is ongoing.

For the extension of the bandwidth, the application of a commercial power meter is being investigated as an alternative to the existing device, instead of adapting the current setup. This device has sufficient bandwidth and solves the problem of the need for external voltage and current scaling devices. Apart from extending the bandwidth of the SAMU, also the generation part of the setup is being extended.

The possibility to lock the reference SAMU to an external 1588 PTP signal has also been investigated.

The first testbed version devoted to the calibration of commercial SAMUs has been designed and built. In preparation for basic calibration of a SAMU according to the IEC 61869-13, software to analyse the sampled values has been developed. A measurement setup was also realised for the calibration of the absolute phase of a digitiser.

The testbed for SAMU calibration has been used extensively during 2023, a total of 4 SAMUs have been calibrated for magnitude and phase errors following IEC 61869-13. The testbed will be further refined based on the experience gained in this work.

Control and analysis software solutions for handling of SV streams

Algorithms for calculating parameters – e.g. RMS value, ratio error or phase displacement – are typically implemented as proprietary solutions in digital substation instrumentation and related test sets. However, their calibration methods have to rely on available SV data streams and separate reference algorithms, which are (i) currently unavailable and not standardised for all parameters under non-synchronous conditions or (ii) are not validated for new data sampling rates up to 96 kSPS.

This project will go beyond the state of the art by developing new data processing schemes and algorithms to accurately characterise the amplitudes, phases, and relevant power quality (PQ) related parameters with complete system-wide uncertainty estimation, thus providing a solid basis for traceable calibrations. All of the project's developed software will be collected and documented in a reference software package that can be used to support a comparison of developed data processing schemes and algorithms. This should enable NMIs and calibration laboratories to better meet end user needs in their transition to digital substations. The comparison results can also be used by standardisation bodies to recommend best validated data processing schemes and algorithms for their intended use.

Software IEC61850-SV-Monitor has been developed and will be used to capture all data from all merging units (MUs), to retrieve the wanted data from the packets, to sort data on MU and Sample Count, to convert samples to RMS values and to present data in tabular and graphic format.

Static, dynamic, linear, and non-linear parameters that need to be estimated from current transformer (CT) and voltage transformer (VT) SV data streams were identified. Based on the results of the questionnaire sent to stakeholders, it was concluded that the power quality parameters, except DC transient, are not relevant for metrological evaluation of CTs and VTs from SV data streams, as the power quality parameters are related to functional equipment tests and not metrological characterisations.

Two optimisation criteria were defined: (i) accuracy and (ii) speed. All algorithms developed were successful for both accuracy and speed, as well as modest or low computation cost. Development focused on resampling procedures, which would enable using Fast Fourier Transform (FFT) for the remaining processing, as well as using spline interpolation. The algorithms are showing very good performance in the current testing campaign. Further to this, a windowed RMS method was adapted for wide range of parameters, including amplitude, active, reactive and apparent power, as well as phase. With proper selection of window and observation time (sample data length), the windowed RMS method was shown to provide fast, robust and accurate parameter estimates.

An algorithm to determine the time constant for DC transient was developed and is currently in the testing phase. In addition, a resampling algorithm using up-sampling and decimating scheme was developed and successfully tested.

Three different algorithms for DC decay are nearly completed in terms of development and testing. In the first algorithm, peaks (positive or negative) are extracted from the waveform and analytically analysed. Although this algorithm is relatively fast, it has a quite large uncertainty (over 2 %). In the second algorithm, digital filters are being used to eliminate the AC signal from the waveform, and then only the DC decay is analytically analysed. This algorithm is also very fast, with improved uncertainty (between 0.1 % and 2 %). The third algorithm is one based on a five-parameter fitting function is fast and reliable (below 0.1 %), but it requires advanced functions in mathematical software.

A concept for uncertainty estimation of the algorithms was also developed.

Several SV data processing paths have also been identified; some of which are using existing methods, and other paths use a novel combination of algorithms to calculate quantities with highest precision. Furthermore, a novel algorithm based on a combination of frequency estimator and resampling was developed and integrated into a testing platform QWTB. For selected paths, the testing of existing and new algorithm was prepared.

Timing networks and calibration method for 1PPS to/from PTP time protocol conversion

Recently, some NMIs (including project beneficiaries VSL and VTT) have developed calibration setups, where the device under calibration uses 1PPS as a timing source and the phase encoded into its SV stream can be compared to the 1PPS pulse front. These reference calibration systems rely on determining the latency of the reference device front-end electronics and compensating for it to produce a 1PPS aligned SV data stream. Similar, commercial devices are required to do the same, as per IEC 61869-9 (Digital interface for instrument transformers) Annex 9B. Several methods for determining the required compensation parameters, and a robust implementation of reference and commercial systems already exist.

The 1PPS timing has been replaced by PTP timing protocol in the new versions of related standards. Therefore, this project will go beyond the current state of the art by developing best practices for the calibration of PTP slave device timing and for verifying leap second insertion in the timing networks. As the PTP timing quality will ultimately depend on all networking components relaying timing packets, the project's focus will not only be on slave devices, but also on master clocks and network switches.

The beneficiaries have studied the technical requirements of devices needed for establishing reliable PTP and SV networking in their institutes and in general use. Inventories of commercially available PTPv2 grandmaster clocks and PTPv2 supporting Ethernet switches were prepared. While the inventories of devices are non-exhaustive, it serves as a good starting point for selecting the equipment needed for the networks. It was noted that practical experience equipment is often required, as manufacturers do not always provide complete product information that may be relevant for the selection of a particular device.

A new PTP-switch has been acquired and the entire PTP chain from master clock to switch output port has been checked with the tools (e.g., PTP trigger devices) developed in this project and found to work well and the SV stream transmission is working as intended. A time and frequency distributor and an Ethernet switch have been acquired and have successfully tested in PTP and SV networking. The PTP internal network for substation synchronization has been reassessed and its short-term behaviour evaluated.

Details of a variety of commercially available network Traffic Access Points (TAPs) for optical networks have been studied. It was found that none of them meet the requirements of this project's objective. Fortunately, the custom device built in the EMPIR project 17IND14 WRITE was found to be a good solution after some modifications. The device is now working correctly and has been calibrated.

PTP trigger devices were designed and are under development at two institutes. The solutions are based on commercially available networking chips and on embedded software development board. During testing, it was found that PTP frame triggers will trigger on any received frames making them impractical. A workaround for this is now under development.

Two PTP servers which could be used as a "golden calibrator pair" have been received, and their calibration is scheduled for the end of March. A new tool for calibrating delays in twisted pair cables and fibres to improve the calibration accuracy of "golden calibrator pair" is under development.

Finally, a report was prepared specifying the proposed "golden calibrator pair" calibration procedures. The selection of equipment for the proposed method is complete and procurement is in progress.

Outcomes and impact

The outcomes of this project will benefit the electrical power industry including digital substation instrument manufacturers and grid operators. The project will also contribute to standards especially those associated with IEC TC 38.

Outcomes for industrial and other user communities

This project will improve, and extend, the current electrical power and energy metrology infrastructure to cover digital substation instrumentation to support the development and improvement of electrical distribution and

transmission grids. Industrial end-users and stakeholders such as TSOs, DSOs and digital substation instrumentation manufacturers will benefit from project outcomes, such as

- (i) enhanced measurement capabilities for the dynamic characterisation of instrument transformers for PQ measurements,
- (ii) a metrological infrastructure for the calibration of SAMUs,
- (iii) reliable time synchronisation (e.g., transmission of SV data and PTP-based timing) between commercial devices, and
- (iv) new test systems for measuring SV-enabled instruments based on IEC 61850-9-2 (Communication networks and systems for power utility automation - 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3), such as energy meters and digital Phasor Measurement Units (PMU).

This project liaises with industrial stakeholders via the formation of a stakeholder committee, which has been set-up and so far has over 30 members from 30 organisations. This group includes representatives from TSOs and DSOs, test and calibration service providers, digital substation instrument manufacturers and standardisation organisations, and will help the project's results to directly impact such representatives.

In addition, this project will also produce and publish 2 good practice guides for end-users (such as digital substation instrument manufacturers, TSOs, DSOs):

- Good practice guide on the calibration of commercial SV enabled instrumentation with sampling rates up to 96 kSPS
- Good practice guide for the calibration of substation instrumentation using PTP timing, including a traceable link between PTP timing and 1PPS reference pulse with a target uncertainty of 100 ns.

Further to this, the consortium has produced and sent e-newsletters to stakeholders on the project (need, objectives, beyond state of the art, consortium). Two e-newsletters were sent to stakeholders in January 2023 and February 2024, and the next e-newsletter is in preparation for May 2024. The e-newsletters will be used to communicate with and disseminate information on the project to stakeholders and to inform them of important outcomes and upcoming events such as the Good Practice Guides and project workshops.

Outcomes for the metrology and scientific communities

The project will develop new and demanding measuring techniques including several important additions and extensions to CMC statements. The power systems scientific community will benefit from these new or enhanced measurement capabilities in areas where scientific information has been scant or lacking. Major scientific impact will be provided via the publication of the key project results in peer review journals and via presentations at key conferences. To date, the project has been presented at the following conferences: ITSF2022 Düsseldorf, Germany, CPEM 2022 Wellington, New Zealand, SEMAG 2023, Poland and SMAGRIMET 2023 Cavtat, Croatia.

The project will also host two workshops which are targeted to standardisation bodies (IEC, CENELEC) as well as industrial stakeholders (e.g., digital substation instrument manufacturers and TSOs), to foster uptake in these communities. The first workshop was organised jointly with the commercial TenneT project in December 2023. Approximately 85 people attend the web-based workshop and it was used to summarise the progress during the first half of the project and to gain feedback from stakeholders. The second workshop will present the results from the project and will highlight the 2 good practice guides developed.

Close cooperation between the project's different types of beneficiaries i.e., from research institutes, digital substation instrument manufacturers and NMIs will also support the dissemination and uptake of its outcomes. The project outcomes will also be shared with the NMI community through the EURAMET Technical Committee for electricity and magnetism (TC-EM), in particular the EURAMET TC-EM "Power and Energy" subcommittee.

A web workshop for projects' stakeholders was arranged jointly with TSO funded DigIT project in December 2023, with 85 participants online. The 9 presentations given during the half day workshop raised good discussions between the participants.

In addition, one-to-one in training was arranged on SAMU calibration for one project partner during his visit. The purpose of the visit was to share the best calibration practices within the consortium.

Finally, the project has provided output to the metrology and scientific communities, via the plans for future research activities in the EMN SEG strategic research agenda and has engaged with EMN-SEG at its general meeting in April 2023.

Outcomes for relevant standards

So far, the consortium has participated in and disseminated information to EURAMET TC-EM (Electricity and Magnetism), BIPM CCEM (Electricity and Magnetism), NEK NK 13/38 – Electricity measuring systems and measuring transformers, IEC TC 13 Electrical energy measurement and control, IEC TC 38 Instrument transformers and SESKO SK 13 Electrical Energy Measurement.

This project will also generate important results on the development of a metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation that will be very valuable to standardisation work within IEC TC 38, CENELEC TC 38, IEC TC 57, IEC TC 77A WG1, WG2 and WG9, IEC TC 42, and CIGRE JWG B5/D2.67. Liaison will be accomplished by members of the project, who are active within the respective committees. The beneficiaries who are members of corresponding technical committees will inform them about the results of this project and will endeavour to ensure they are incorporated in any updates to the standards or guidelines.

Project overview and especially project progress on substation timing calibration was presented to standardization committee members during the IEC TC 38 workshop on October 2023.

Longer-term economic, social and environmental impacts

This project supports the long-term transition of the European power grid from analogue to digital control. The use of next-generation instrument transformers and PMU equipped substations is the prerequisite for successful integration of wide-scale connection of decentralised renewable energy sources in the High Voltage (HV) distribution and transmission grid. These next generation digital substations will also help to ensure the stability of the European power grid. European power grids are under increasingly complex and challenging conditions due to the societal desire for the large-scale introduction of renewable energy sources. By supporting the stability of the grid, more electricity supplied by renewable energy sources can enter into Europe's energy supplies, meaning that less conventional carbon-rich electricity generation (i.e., coal), is required and less CO₂ emitted.

Reliable electrical delivery is also one of the key needs in modern society e.g., even our water supply depends on the supply of electricity. This means that when black-outs and brown-outs occur, they result in major costs and disruptions to society. HV transmission grids are crucial for the electricity grid infrastructure; however, the current electricity grid infrastructure is aging. The ageing of the first generation of instrumentation is already stressing the network and impacting the reliability of our daily electricity supply. This project will help support the reliability of Europe's electricity supply by through the implementation of new digital substation instrumentation and HV transmission grids.

The project's outcomes will also support the long-term competitiveness of the European electrical industry, in particular digital substation instrumentation manufacturers, by providing them with the metrology tools to unambiguously prove the quality of their equipment. High quality equipment is one of the prime selling points for European industry and should provide a decisive competitive advantage with respect to other lower-cost but lower-quality equipment.

List of publications

- [1]. Saldana, Jose, Oliván, Miguel A (2024) 'Lossless and Stateless Compression of IEC 61850 Sampled Values Flows', *IEEE Transactions on Power Delivery*, 39(2) p. 1314-1317. Available at <https://zenodo.org/records/10629711>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2022, 36 months	
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Project website address: https://www.ri.se/en/digital-it			
Chief Stakeholder Organisation: IEC TC 38		Chief Stakeholder Contact: Volker Leitloff	
Internal Beneficiaries:		External Beneficiaries:	Unfunded Beneficiaries:
1. VTT, Finland		9. CIRCE, Spain	12. OMICRON, Austria
2. CMI, Czechia		10. LeftRight, Slovenia	13. Statnett, Norway
3. GUM, Poland		11. Lukasiewicz-ITR, Poland	
4. JV, Norway			
5. Metroserf, Estonia			
6. RISE, Sweden			
7. SIQ, Slovenia			
8. VSL, Netherlands			

Publishable Summary for 21NRM03 MEWS Metrology for emerging wireless standards

Overview

Complex wireless technologies underpin the Internet of Things (IoT) and fifth and sixth generation (5G and 6G) mobile networks. These 'new radio' technologies require improved underpinning normative wireless standards for their radio signals, systems, and the transmission environments used, and for the radio frequency exposures created. Current telecommunications sector challenges include a lack of accurate, fast, low-cost, and traceable methods for manufacturers to demonstrate that 5G/6G product verifications match customer specifications. This project will develop the practical and efficient measurement methods required to enable normative standards for wireless channels up to sub-THz, and for radio frequency exposure assessment to better match rapidly emerging radio technologies for 5G/6G products and system over-the-air testing.

Need

The digital economy and high bandwidth mobile communications are essential tools for wealth creation in Europe and will enable an estimated USD12.3 trillion of global economic output by 2035. As digital connectivity becomes more and more ubiquitous, and offers higher capacity, it will become the new 'lifeblood' of the digital economy and connected society with over 8.9 billion mobile subscriptions envisaged by 2025. Emerging wireless technologies with Gbps connectivity has the potential to improve communications for 100 million students, more than 70 million workers, almost 2 million doctors and more than 2.5 million patients in hospitals within the EU alone by 2025. For this to happen a robust measurement infrastructure for emerging wireless technologies needs to be developed and then incorporated into relevant normative standards, e.g. CENELEC, IEC, ETSI, and IEEE, so that telecommunications manufacturers can have confidence that ICT products meet customer specifications.

The European Digital Agenda is driving the exploitation of Information and Communication Technologies (ICTs) by fostering innovations and economic growth, with a crucial role being played by the European telecommunications industry in the development of emerging wireless technologies for IoT and 5G/6G mobile networks. The rollout of these networks and large-scale deployments of cellular IoT will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. Metrology has a pivotal role to ensure product quality and end-user confidence, and ultimately to improve the competitiveness of European Industry.

With the increasing adoption of complex new radio signals and large-scale multi-antenna technologies at different radio frequency (RF) bands in emerging wireless systems, manufacturer product verifications have become very time consuming and involve complicated procedures and equipment, leading to high testing costs. International standards bodies (e.g. ETSI, 3GPP), the telecommunication industries and research communities are now actively seeking improved process control on New Radio Over the Air (NR OTA) methods (*Objective 1*). Also, sub-THz wireless radio propagation channel characterisation (*Objective 2*) is currently an active topic being studied by ITU and IEEE standard development organisations, but there is a need for real-world empirical measurement data to support this R&D advancement toward 6G definitions and new product development. Furthermore, there is no reliable method to measure the RF exposure of 5G new radio systems. Importantly, CENELEC, IEC and IEEE international standards are actively seeking improved process control for addressing the product testing time-burden issue when using current RF exposure assessment methods (*Objective 3*). Hence, there is an immediate need for NMI-level metrology research to improve measurement capabilities and to provide underpinning metrology to input to the relevant standards to support the

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: June 2024

competitiveness of European industry. The work proposed in this project aligns with broader European visions, as outlined in the European Commission Strategy – e.g. “Digital Single Market”.

It is recognised that no single NMI has, or will have, the capability to deliver all the work in this project. Our strategy, therefore, is to bring together the EU’s leading NMIs and academics in this area to build capability across all the participants that fully aligns with stakeholder and standardisation measurement needs. This approach aligns with the European Partnership on Metrology’s goal of promoting collaborative research in the most demanding fields of industrial metrology by exceeding the current state of the art.

Objectives

The overall objective of the project is to develop practical and efficient traceable measurement and characterisation methods for use in the emerging wireless standards being developed by ETSI, CENELEC, ITU, 3GPP, IEC, IEEE and other related groups. The specific objectives of the project are:

1. To develop traceable cost-effective NR over-the-air measurements to 30 GHz for: (i) new radio over-the-air system performance evaluation of sub-6 GHz and mm-wave MIMO systems with consideration where feasible of RTS, MPAC and RC+CE based methods taking into account ETSI TR 38.827 requirements; (ii) new radio over-the-air RF parametric conformance measurements of sub-6 GHz MIMO and mm-wave massive-MIMO systems using selected power-related parameters (e.g. TRP, EIRP) with uncertainty evaluations with consideration where feasible of DFF, IFF, NF-FF, mid-field and RC methods taking into account ETSI TR 38.810 and TS 38.141-2 requirements. In addition, to evaluate the methods via international comparison exercises.
2. To characterise the complex real-world sub-THz wide-bandwidth radio propagation channel suitable for the planning of short/medium-range wireless communication and active services operating up to 750 GHz for practical realisation for 5G/6G communications by: (i) the development, and verification of three traceable channel sounding testbeds (operating up to 330 GHz, 550 GHz and 750 GHz respectively), (ii) the performance comparison of these testbeds with the results added to an open access database and (iii) the validation of the test beds via channel modelling, and potentially using novel approaches based on band stitching techniques and optical cable solutions.
3. To develop and evaluate measurement protocols to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements, including traceability. This will include (i) developing a measurement methodology for measuring PD exposure levels of 5G new radio base stations for incorporation into Good Practice Guidance and for submission to, e.g. IEC 62232, and IEC 62669 for their consideration as an input to Technical Specifications and (ii) developing a standardised measurement procedure for the quantification of RF exposure in terms of SAR and Absorbed Power Density measurements of 5G new radio mobile phones suitable for submission to international standardisation bodies, e.g. CENELEC CLC/TC 106X, IEC TC106 MT3 and JWG12 for their consideration as an input to standards.
4. To contribute to the standards development work of the technical committees of the relevant standards developing organisations, e.g. CENELEC CLC/TC 106X, IEEE 802.15 SC THz, 3GPP and ETSI ISG mWT and to ensure that the outputs of the project are aligned with their measurement needs, communicate quickly to those developing the standards and to those who will use them (e.g. the telecommunications industry), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Efficient over-the-air testing, and RF exposure measurements of 5G new radio systems with many advanced features, is needed to efficiently and cost effectively assess complex new radio system performance and product conformance to specifications. Also, new knowledge of wide bandwidth sub-THz radio propagation channel measurements for R&D advancement towards 6G definitions and new product development is needed. This project is addressing these by building progress beyond the state of the art from previous projects that included some preliminary 4G over the air studies at sub-6 GHz and 5G new radio signals at 30 GHz, respectively.

Traceable cost-effective NR over-the-air measurements to 30 GHz (Objective 1)

3GPP and ETSI have been working on the performance metrics, measurement methodologies, and validation procedure for the MIMO over the air evaluation of 5G new radio user equipment and base stations. For 5G new radio (NR) performance testing, only the multi-probe anechoic chamber (MPAC) and radiated two-stage (RTS) methods have been considered. In addition, for 5G new radio RF parametric conformance measurements, consideration is only given to direct far-field (DFF), indirect far-field (IFF) and near-field to far-field transformation (NF-FF) techniques. This project is developing a more efficient and cost-effective over-the-air radiated testing metrology for RF conformance metrics and end-to-end performance metrics for new radio systems at both sub-6 GHz and mm-wave bands (up to 30 GHz). The main developments are:

A cost-effective wireless solution using a standalone phase/amplitude control matrix has been implemented. This reduces previous cable resource requirements whilst achieving efficient high-order MIMO at sub-6 GHz.

A 5G Testbed (FR1) using 5G NR SDR and emulator on PXIe VST hardware was completed, providing a versatile SISO platform,

A demonstration of a wireless solution for mm-wave with antenna polarisation/pattern discrimination for wireless cable connection was conducted. Passive measurements showed better than 30 dB isolation.

A test zone validation algorithm using directive antennas was developed, overcoming limitations of biconical antennas and enabling 3GPP NR performance tests through a two-step method (channel measuring & synthesising).

An NR beamforming antenna array system for both sub-6 GHz and mm-wave was established. This includes the development of a wideband NR signal generation testbed for sub-6 GHz MIMO, and the integration of a controllable beamformer for mmWave mMIMO testing.

A wireless cable OTA testing solution for high-order MIMO mobile terminals was designed and developed, demonstrating its potential for standardisation of future radio device performance testing.

Traceable sub-THz wide-bandwidth radio propagation channel measurements to 750 GHz for 6G (Objective 2)

The current state of the art for THz channel sounding is up to 330 GHz and it is limited to measurement scenarios with a very short measurement range i.e. to 1 m. There is still a lack of measurement-based knowledge of the characteristics of many typical real-world deployment scenarios e.g. indoor/outdoor at different sub-THz and mm-wave frequencies. This project is extending the state of the art by putting in place THz channel sounding up to 750 GHz for both indoor and outdoor environments, enabling users in the wireless communication industry to characterise propagation channels at these very high frequencies. The main developments are:

Novel VNA techniques for mmWave and sub-THz (20 GHz - 750 GHz) were developed, enabling characterisation and capture of channel parameters in various environments, paving the way for improved sub-THz radio link models for 6G and beyond.

Long-range sounders were established for sub-6 GHz, mmWave, and sub-THz, contributing to long-range, high-data connections for future 6G radios.

A MIMO channel sounder has been developed at 28 GHz together with a band-stitching algorithm for extended range measurements, and an antenna-in-package solution for dynamic scenarios was demonstrated.

Cross-referenced techniques across 3 European institutes were established, demonstrating confidence in proposed metrological techniques for future standardisation of sub-THz and THz communication in next-generation networks.

Strategies to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements (Objective 3)

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) produced new guidelines in 2020. According to these guidelines, the physical quantity of interest for near field exposure radiation above 6 GHz is now the Absorbed Power Density in W/m², whereas for radiation below 6 GHz it remains the Specific Absorption Rate (SAR) in W/kg. Similarly, the physical quantity of interest for far field exposure radiation above 2 GHz is now the incident power density in W/m² whereas for far field exposure radiation below 2 GHz it is the

incident E-field in V/m or the incident H-field in A/m. The procedure to determine the power density in a way that it is traceable to the SI system of units has yet to be developed. The conversion of E-field to power density requires an assumption of the proportionality of the H-field to the E-Field, which is only valid for pure plane waves as in far field. This conversion is therefore not applicable for near field radiation. The current state of the art for new radio RF exposure measurement is up to sub-6 GHz (under the EMPIR SIP 18SIP02 5GRFEX that includes an experiment-based RF exposure study of the stochastic nature of massive MIMO system at sub 6 GHz). This project is extending the state of the art by putting in place traceability for RF exposure measurements up to 26 GHz for 5G base stations, and for Absorbed Power Density (APD) measurements up to 40 GHz for 5G mobile phones. The main developments are:

An algorithm for demodulating 5G NR signals (including synchronisation PSS, SSS, and demodulation reference DM-RS) and post-processing for improved signal processing have been developed, and have shown that PSS and SSS are successfully detected.

SI traceable measurements have been carried out, demonstrating improved precision for quantifying and assessing RF exposure from 5G base stations (sub-6 GHz and mmWave).

A reference setup has been evaluated across various bands and scenarios, leveraging LTE experience and different measurement protocols and scenarios for assessing RF exposure from 5G base stations have been defined.

Machine learning models have been developed for probe linearisation, and implementation of Absorbed Power Density (APD) calibration and its validation at specific frequencies and release of first APD measurement system (24-30 GHz) enabling compliance testing with new APD limits.

Outcomes and impact

The consortium has participated in, and in some cases presented the project's activities at, seven meetings of technical committees or working groups of European and international standards organisations, and has even contributed to IEC TC 106 APD, ETSI ISG THz and ITU THz and Wireless technology standards documents. Progress results have been presented at various conferences and workshops. Eighteen peer-reviewed open access papers were published. Other actions included the creation of a website, a flyer, a LinkedIn group (with 23 views/members), a periodic newsletter with the first issue sent in December 2023, and the organisation of 4 convened sessions and a dedicated workshop at the 18th European Conference on Antennas and Propagation EuCAP2024. In addition, a Technical and Stakeholder Advisory Group has been set up, with 16 members already, and a collaboration with an SME has been initiated. Finally, initial KERs have been identified and a plan for their follow-up has been drawn up.

Outcomes for industrial and other user communities

This project will enable efficient, accurate and traceable measurements covering all aspects from the new radio signals, systems, antennas, propagation environments and public exposure at a wide range of frequencies up to sub-THz. This will have direct outcomes on wireless communications and electronics industries by ensuring product quality and end-user confidence. Notable examples include virtual and augmented reality, autonomous driving, remote surgery, artificial intelligence, smart manufacturing, unmanned aerial vehicles (UAV), IoT and vehicle-to-everything.

The establishment of measurement traceability and the improvement of measurement accuracy will enable manufacturers to provide confidence in their specifications. This plays a key role in the customer/supplier relationships, for which products need to be demonstrated as 'meeting specification', regardless of who is carrying out the test or when/where the test is being performed. The outcomes of this project will allow emerging wireless product manufacturers to specify their products more precisely, leading to systems with better performance. This in turn will boost the product yields for the manufacturers and potentially reduce prices for customers as well as enhancing user experiences.

This project will achieve new measurement capabilities by extending the current capabilities of the participating NMIs, to 750 GHz for radio propagation, to 30 GHz for new radio over-the-air measurements and to 40 GHz for new radio RF exposure measurements. This will lead to greatly improved access to, and dissemination of, measurement traceability for European NMIs, accredited testing and calibration laboratories and the manufacturers of test instrumentation. This will be beneficial for all end-users, including customers and suppliers of emerging wireless devices and systems.

The project has designed and implemented a new traceable calibration concept for APD probes and produced a new generation of APD probes for near-field measurements for the millimetre-wave range that will pave the way to future uptake by manufacturers and testing laboratories in the telecommunications field. This contributed to the release of the first APD measurement system.

Outcomes for the metrology and scientific communities

This project involves five European NMIs with world-leading capabilities, along with five world-leading academic, and seven key industrial unfunded beneficiaries, who bring in their specific knowledge, and measurement instrumentation to these emerging technologies. Together these provide a strong coherent consortium that will enhance the quality of the research outputs, and this will maximise the overall outcomes from the project. The outcome will be to propose changes to NMI calibration and measurement capabilities to provide the underpinning metrology that supports the European emerging wireless technology research effort and to keep the focus within Europe. During the lifetime of this project, preparatory tasks will be undertaken to subsequently establish a coordinated network of NMIs that will provide comprehensive measurement capability based on the scientific activities in this project, and, in other earlier and current European projects (specifically, previous EMRP).

The project was presented at the International Metrology Congress and at the EURAMET TC-EM Subcommittee (SC) Radiofrequency and Microwave (RF&MW) Meeting, where representatives from several European NMIs not involved in the project expressed their interest and expectations in the project results.

Outcomes for relevant standards

The NMI-level metrology research performed in this project, will provide the underpinning metrology as input to the relevant standards in this area in order to support the competitiveness of European industry. The project outcomes will enable standard bodies to implement practical and the efficient measurement methods required to enable normative standards to better match rapidly emerging radio technologies, which was not previously possible. This project will make substantial contributions to the following international standards and related documents:

- (i) International standards developed by ETSI/3GPP: TS 38.141-2, TS 38.151, TS 38.161, TS 38.521-1, TS 521-2, TS 521-4
- (ii) International standards developed by IEEE: IEEE 802.15.3d, IEEE 1720
- (iii) International standards developed by IEC: IEC TC106 MT3 and JWG12
- (iv) International standards developed by CENELEC: CLC/TC 106X
- (v) International standards developed by ITU: ITU-R IMT-2020, ITU-R SM.2352, ITU-T SG5

This project will also have indirect outcomes on the European standards being developed by the European Telecommunications Standards Institute (ETSI) through 3GPP. These include 3GPP TR 38.827, 3GPP TR 38.810, 3GPP TR 37.842, 3GPP TS 38.101-1, 3GPP TS 38.101-2, 3GPP TS 38.101-4, 3GPP TS 38.104, 3GPP TS 38.141-2, ETSI EN 302 686 and ETSI EN 302 550. Progress and output from this project will be disseminated to the above standards bodies and committees, via representatives in the consortium who are involved in these standards bodies.

The project partners involved in technical committees and working groups of international and European standards development organisations, such as ETSI, IEEE and ITU, have already contributed to the development of new or existing standards documents, promising potential exploitation of the project results. To date the results achieved by this project relating to APD probe calibration (Objective 3) have been included in the IEC TC 106 JWG12 draft technical report "Evaluation of Absorbed Power Density Related to Human Exposure to Radio Frequency Fields from Wireless Communication Devices Operating between 6 GHz and 300 GHz".

Longer-term economic, social and environmental impacts

Economic: The digital economy, and high bandwidth mobile communication, are essential tools for wealth creation in Europe. Digitisation of products and services has a significant economic impact, with more than 110 B€ extra revenue added to industry per year in Europe. To date, over 80 % of Europeans have a mobile phone and 50 % a smartphone. 315 million Europeans use the internet every day. These figures are constantly growing and have been illustrated by a demand-led compound data growth rate of 40 % per year. The

measurement science generated by this project will pave the way for the development of emerging applications using the future generation wireless network including virtual and augmented reality, autonomous driving, remote surgery, smart manufacturing, UAV, IoT, Vehicle-to-Everything and security imaging. This will enable European businesses to move into these areas with confidence and it will ensure a strong competitive advantage over organisations outside the European region, and it will attract business from global markets.

Health and Social Care: The impact of emerging wireless technologies will extend well beyond telecommunications, and it is increasingly underpinning all aspects of health and social care activities. This will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. It is envisaged to provide a universal communication environment that enables us to address the wider societal challenges, such as transport, automotive, safety, employment, health, environment, energy, manufacturing and food production. Furthermore, rigorous scientific evidence on RF exposure issues will enable effective wireless system deployment to be supported that balances user experience and public safety.

Environment: Space radiometers play a key role in Earth monitoring, which provides information about global climate change and weather forecasting. This project will facilitate more accurate and traceable measurements at millimetre-wave and terahertz frequencies, yielding radiometers with better performance. The energy efficiency of systems will also be improved as a result of more accurate measurements. The average electromagnetic radiation intensity has been steadily increasing, fuelled by the evolution of wireless communications for applications like IoT, 5G and beyond. To reduce the impact of electromagnetic fields on the environment, it is therefore important to decrease the transmitted power of wireless communication systems and to measure power density as precise as possible, which this project will underpin.

The project's developments in efficient OTA measurements, sub-THz wide-bandwidth channel measurements, and RF exposure assessment, as described in the results above, are likely to drive innovation within the wireless technology industry by enabling new applications and markets. These developments may also enhance communication, healthcare, and safety, while potentially contributing to environmental goals through improved climate monitoring and energy efficiency.

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
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Project website address: https://projects.lne.eu/jrp-mews/		
Chief Stakeholder Organisation: CENELEC		Chief Stakeholder Contact: Matthias Meier
Internal Beneficiaries: 1. LNE, France 2. CMI, Czechia 3. RISE, Sweden	External Beneficiaries: 4. AAU, Denmark 5. IMTelecom, France	Unfunded Beneficiaries: 6. Anritsu AU, Austria 7. Keysight BE, Belgium 8. MVG, Italy 9. NNF, France 10. ZTE AB, Sweden
Associated Partners: 11. BJTU, China 12. CAICT, China 13. METAS, Switzerland 14. NPL, United Kingdom 15. QMUL, United Kingdom 16. SPEAG, Switzerland 17. SURREY, United Kingdom		

Publishable Summary for 21NRM04 BiometCAP

Protocol for SI-traceable validation of methods for biomethane conformity assessment

Overview

The conformity assessment of biomethane requires further standardisation in order to support Europe's green energy future. The overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32 % in the RED II directive [Directive (EU) 2018/2001, 2018]. This project will deliver accessible traceability to the stakeholder community by developing efficient and cost-effective methods for the preparation of traceable gas transfer standards for the performance evaluation of biomethane monitoring systems. Using these, a robust performance assessment protocol will be developed and validated in order to benchmark and characterise analytical systems (e.g. gas analysers). The outputs, including trial applications, will be directly fed into standardisation development. This project will bridge the gap between previously developed primary standards and the industry's need for accessible, traceable performance evaluation against a validated protocol.

Need

Biomethane is already used widely within Europe as a means to sustainably displace fossil fuels. Its usage is projected to increase significantly (doubling by 2030 from the current 26 Terawatt-hour (TWh) produced in Europe) [EBA "European Biogas Association Statistical Report: 2019 European Overview", 2020] as a result of European green energy targets [European Commission, A European Green Deal, 2019]. Biomethane quality monitoring is essential to prevent damage to the existing natural gas infrastructure and to end user appliances that can be caused by harmful impurities in biomethane. In addition, these impurities need to be kept below limit thresholds (as specified in EN 16723 for gas grids [EN 16723 1 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network Part 1: Specifications for biomethane for injection in the natural gas network, 2016] and vehicles [EN 16723 2 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network Part 2: Automotive fuel specifications, 2017]).

Reliable and traceable purity measurements can only be obtained with equipment of known performance, from which the sensitivity, selectivity, precision and bias have been traceably evaluated (as required under e.g. ISO/IEC 17025 §7.2 [ISO/IEC 17025, Testing and Calibration Laboratories, 2017]) (Objective 3). Instrument manufacturers and end users require a standardised protocol (Objective 2) in order to meaningfully demonstrate instrument performance in both laboratory and field settings. Despite similar approaches existing for other green fuels, e.g. hydrogen in the form of ISO 21087 [ISO 21087 Gas analysis — Analytical methods for hydrogen fuel — Proton exchange membrane (PEM) fuel cell applications for road vehicles, 2019], a suitable biomethane evaluation protocol does not yet exist.

An additional challenge is bias prevention, as existing measurement methods (e.g. as developed in EMPIR JRP 16ENG05 Biomethane) have not been traceably tested for cross-interference bias caused by gas matrix and impurity variation. This type of selectivity evaluation is essential to prevent bias in reported results, to prevent interruptions in the supply of biomethane into the European gas infrastructure (caused by over-reporting), and to prevent damage to infrastructure (caused by under-reporting).

To deliver this on a practical level, cost effective transfer standards need to be developed to disseminate traceability from the primary standards in an accessible format for the biomethane industry, which includes many small-scale producers (Objective 1). These transfer standards need to be fit-for-purpose in terms of measurement uncertainty ($\leq 10\%$) and shelf life (≥ 12 months). Improving accessibility to gas standards and a

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: May 2024

validated protocol for their application will allow for a safe and effective expansion of the biomethane industry within Europe.

Objectives

The overall objective of this project is to support the development of standardisation and to provide the traceability, reliability and characterisation necessary for the conformity assessment of biomethane.

The specific objectives of the project are:

1. To develop and validate methods for the static and dynamic preparation of gas transfer standards containing different groups of impurities. These should be suitable for use in the SI-traceable validation and performance evaluation of current and future analytical instruments and methods that are used in the conformity assessment of biomethane in accordance with EN 16723. In addition, this should include determining the key metrological parameters of each method. Uncertainties of 1 % - 10 % are targeted for EN 16723 limit values.
2. To develop a comprehensive protocol for the validation and performance evaluation of the analytical instruments and methods that are used in the conformity assessment of biomethane (applicable to both current and future methods). The validated and implemented methods should be able to generate reproducible and SI-traceable measurement results and a NWIP and draft ISO text should be submitted to ISO.
3. To use the protocol, developed in objective 2, to evaluate the performance of commercially available industrial gas analysers, based on e.g. spectroscopy or gas chromatography, which are used for laboratory and field-based biomethane (test) measurements. The protocol should also be used to evaluate all relevant measurement methods. A review will be undertaken to evaluate its effectiveness and reproducibility across a wide variety of methods and compounds.
4. To maintain constant contact with the EMN for Energy Gases and collaborate with the technical committee ISO/TC193/SC1/WG25 "Biomethane" and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs and are incorporated into future standards at the earliest opportunity and that user training and knowledge transfer is maximised throughout the project. This will include, in particular, the protocol developed in objective 2.

Progress beyond the state of the art and results

To develop and validate methods for the static and dynamic preparation of gas transfer standards containing different groups of impurities. These should be suitable for use in the SI-traceable validation and performance evaluation of current and future analytical instruments and methods that are used in the conformity assessment of biomethane in accordance with EN 16723. In addition, this should include determining the key metrological parameters of each method. Uncertainties of 1 % - 10 % are targeted for EN 16723 limit values. (Objective 1)

This project will develop novel, cost effective solutions in the form of multi-component gas standards and improved dynamic methods for the preparation of gas transfer standards, with a focus on the impurities and limit levels specified in EN 16723. This cost-effective approach will allow laboratories to perform verification, validation and quality control as required by, e.g. ISO/IEC 17025, with reduced and affordable costs, thus increasing access to traceability for the industry. These standards will also resolve the issue of some standards not being available for field use on biomethane sites due to their complexity, non-portability and cost.

Novel cost-effective standards will also be developed for the evaluation of the effects of the variable biomethane gas matrix and cross-interferences caused by impurities simultaneously present in biomethane. This project is the first research project addressing this issue in full and the project's output will help to secure the reliability of the analytical measurements of the impurities in biomethane, avoiding biases that are commonplace (e.g. terpenes/siloxane interferences via certain GC methods and methane interference with certain spectroscopic methods).

A stakeholder survey and consultation was completed, the outcome of which was shared with the participants and the stakeholder committee. The results were used to define a specification for the compositions of static and dynamic standards which will be prepared within the project. The majority of the static gas standards have been produced according to plan and have been scheduled for dispatch to relevant participants. The ammonia and hydrogen chloride mixtures are currently in the planned validation stage. Using static gas standards, NPL

have completed the assembly and initial validation testing of a dynamic system. An existing system, based on thermal mass flow controllers, was modified to make it portable for use in the field. VSL has performed some initial tests for multi-point calibration with biomethane, carbon dioxide, nitrogen, and hydrogen using the dynamic preparation facility. Further tests on the calibration and to assess the calibration against VSL's own static gas standards are ongoing. The development of the portable optical gas standard system is underway at PTB. The liquid evaporative generator to dynamically generate gas standards has been optimised by VTT and it is currently being used to generate data. The validation of these systems is underway.

To develop a comprehensive protocol for the validation and performance evaluation of the analytical instruments and methods that are used in the conformity assessment of biomethane (applicable to both current and future methods). The validated and implemented methods should be able to generate reproducible and SI-traceable measurement results and a NWIP and draft ISO text should be submitted to ISO. (Objective 2)

Currently, gas analysers for biogas and biomethane applications cannot be reliably evaluated for performance. ISO 10723 [ISO 10723, Natural gas — Performance evaluation for analytical systems, 2012] describes the performance evaluation for analytical systems for natural gas composition, and ISO 21087 is in place for hydrogen applications, however methods and protocols for biogas and biomethane applications still need to be developed. This project will develop a robust protocol for the sampling, analysis and performance evaluation of analytical instruments (gas analysers) and methods that are used for biomethane conformity assessment. The protocol will be designed to be suitable for current and future measurement techniques.

The consortium has now produced the protocol for the validation and performance evaluation of the analytical instruments and methods that are used in the conformity assessment of biomethane as a living document which will be improved once the participants have validated it for different species using a wide range of validated methods. The consortium has published 3 open access reports summarising the requirements for the protocol (validation parameters, existing protocols, and standardised methods), the requirements for sampling including recommendations for maintaining the integrity of the sample and the requirements for laboratory and field validations of the instruments, all available on the BiometCAP website. A key aspect of the sampling of biomethane highlighted in the reports is the risk of losing impurities through adsorption on the vessel's wall or in the sampling line. The selection of appropriate materials for the sampling vessel and sampling line is crucial and a material compatibility table mostly based on outcomes from previous projects has been proposed (even though not yet extensively filled) to help in this choice. Validation of the performance assessment protocol is underway by the participants for total silicon, siloxanes, ammonia, HCl, halogenated VOC, terpenes, hydrogen carbon monoxide, oxygen and nitrogen.

To use the protocol, developed in objective 2, to evaluate the performance of commercially available industrial gas analysers, based on e.g. spectroscopy or gas chromatography, which are used for laboratory and field-based biomethane (test) measurements. The protocol should also be used to evaluate all relevant measurement methods. A review will be undertaken to evaluate its effectiveness and reproducibility across a wide variety of methods and compounds. (Objective 3)

The performance assessment protocol will be validated using lab-based analysers, and traceably validated methods that were previously developed as part of targeted research (e.g. EMRP JRP ENG54 Biogas, EMPIR JRP 16ENG05 Biomethane). The application of the performance assessment protocol will then be expanded to industrial analysers and a review will be undertaken of the results of its application, comparing the variables of location, analyte and technique in order to produce a good practice guide for the repeatable and accurate implementation of the performance assessment protocol. Such a comparison has not been undertaken for the biomethane industry and the results will provide a valuable route for more solutions to enter the market and for stakeholder knowledge to be enhanced.

To expand the application of the performance assessment to industrial analysers, the following instruments have been selected: a micro-GC-TCD (from DTU), a FTIR analyser (from TFS), a OFCEAS analyser (from VTT) and a MS analyser (from DTU). This covers the three analysis principles identified in the project (spectroscopic-based instruments, spectrometry-based instruments and gas chromatography-based instruments). Technical discussions continued with the biogas plant owners and an additional biogas production site was identified in Finland for the site measurements. The two biogas production sites identified in Denmark are in Bevtøft and Lille Skensved. The three biogas production sites identified in Finland are in

Riihimäki, Lahti and Lohja. Field site measurements have been scheduled. The measurements are planned for August 2024 in Finland, and for the end of September 2024 to October 2024 in Denmark.

Outcomes and impact

To promote the project, and to share insights generated throughout the project, the project was introduced to scientific and industrial end-users. One paper has been published in Accreditation and Quality Assurance. One presentation was made at the 2023 Emerging Fuel Symposium conference in USA, and a poster was presented at a workshop organised by the EMN for Energy Gases in Portugal. A presentation was made at the international Gas Analysis Workshop 2024 in Paris and the 'best lecture in metrology prize' was awarded to Lucy Culleton of NPL for her presentation describing the work done in the project. A poster was presented at a workshop organised by the EMN Energy Gases. Another poster was presented at the International Conference on Measurements of Energy (ICME2023) in September 2023 in Braunschweig, Germany. The project and progress were presented at the TC-MC meeting in Delft, The Netherlands, in February 2024 and at VSL Themadag in September 2023 in Delft. The progress made in the project has been regularly presented to the ISO/TC 193 WG25. The project was also introduced to the WG Biomethane of the GERG network.

Outcomes for industrial and other user communities

By gaining an insight into the user communities measurement needs, the project's outcomes will enable fit-for-purpose biomethane conformity assessment measurement services to be provided to industries, testing laboratories, research organisations and other end-users. Such services will include: a) calibration gas mixtures b) calibration and measurement facilities and services c) performance evaluation of gas analysers; d) direct characterisation of biomethane quality in the field; e) proficiency testing; f) consultancy and g) training. Use of the good practice guide produced by the project will allow end users to have an accessible format to refer to for use with biomethane conformity testing, thus allowing the project's outcomes to be shared. Accreditation can be sought against e.g. ISO 17025.

Instrument (e.g. gas analysers) and sensor manufacturers will receive access to a performance assessment protocol which they can use to benchmark their products and use during the product development process as a means of quality control. Their customers will be able to utilise the performance assessment protocol for their own quality control checks when e.g. developing and characterising methods.

Biomethane producers will be able to use the performance assessment protocol in combination with transfer standards and training material outputs to repeatably and accurately quantify analyser performance, which will reduce the opportunity for measurement bias and improve the efficiency of biomethane production. This will ensure that they meet the quality assurance requirements of e.g. national regulations.

As outlined above, it is anticipated that a major outcome of this project will be the widespread uptake and use of the biomethane performance assessment protocol for biomethane conformity assessment throughout Europe and globally. Another outcome will be the increase in new industrial products and services for biomethane quality monitoring using the new solutions developed in this project (e.g. traceably validated industrial biomethane measurement systems as validated within this project).

Outcomes for the metrology and scientific communities

Laboratories, research organisations and academia will be able to use the state-of-the-art gas transfer standards and the performance assessment protocol developed within this project to perform further research within the biomethane purity area to support the development of new biomethane measurement technologies. Using the outcomes from this project, their performance will be able to be traceably quantified to the SI.

Metrology institutes will have new capability in the form of gas transfer standards and a performance assessment protocol by which to evaluate further techniques and methods they wish to develop within the biomethane area for research and delivery of measurement services to industry. This knowledge will be transferred from the experienced to the less experienced metrology institutes.

Outcomes for relevant standards

The project's outputs will provide direct input to ISO/TC193/SC1/WG25 "Biomethane" by providing them with a validated protocol for the sampling, analysis and performance evaluation of gas analysers. The results of the performance evaluation of the industrial gas analysers will give a realistic overview of (industrial) measurement capabilities, which will allow standards to be tailored to the real needs of industry and it will promote their

widespread uptake. The protocol and method developed for the performance evaluation of gas analysers will be submitted to ISO/TC193/SC1/WG25 for consideration as a new ISO standard (in the form of a New Work Item Proposal (NWIP) and draft ISO standard text). The results obtained from the project will also be disseminated to CEN to enable it to update EN 16723 under its mandate M/475.

The project will also provide input to the activities of other committees, such as ISO/TC158, CEN/TC408, BIPM CCQM Gas Analysis Working Group (GAWG), EURAMET/Metchem SC-GAS, and national working groups and mirror committees. The project was presented to the national standards development organisation of the Netherlands; NEN in March and September 2023, and to the national standards development organisation of Sweden, SIS in September 2023. The project and the first outcomes were presented to EURAMET TC-MC in February 2024 in Delft, The Netherlands.

Longer-term economic, social and environmental impacts

In the longer term, the project's outputs will enable fit-for-purpose services to be provided to industries, testing laboratories, research organisations and other end-users. End users will be able to verify the performance of their measurement equipment with a validated protocol using the developed gas transfer standards. The need for fewer gas transfer standards will significantly lower the cost of biomethane conformity assessment, making biomethane production cost-effective for small producers. These service receivers will be able to undertake e.g. SI-traceable calibrations of equipment and the calibration of gas mixtures, to improve the quality of their measurement results, and they will be able to use traceable and cost-effective gas transfer standards for measuring impurities in biogas and biomethane.

The accurate measurement of trace-level toxic impurities in biomethane will, in the longer term, ensure that regulations limiting the contents of these compounds to safe (non-toxic) levels can be enforced robustly.

This project will accelerate the increased use of biomethane and upgraded biogas and it will enrich the European natural gas supply chains. Therefore, it will also help to reduce Europe's dependence on natural gas imports and it will promote the realisation of the EU target on Renewable Energy.

Increased use of biomethane will help reduce emissions of greenhouse gases and reliance on fossil fuels, as biomethane is produced from renewable sources, such as organic waste, landfills, pulp sludge or manure. Its use in road vehicles will significantly limit harmful emissions. This project will assist the EU in moving towards solving the major global problem of decarbonisation.

List of publications

Arrhenius, Karine et al (2023) 'Need for a protocol for performance evaluation of the gas analyzers used in biomethane conformity assessment', *Accreditation and Quality Assurance*. Available at <https://doi.org/10.1007/s00769-023-01562-x>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months	
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Project website address: www.npl.co.uk/euramet/biometcap			
Chief Stakeholder Organisation: Institute for Energy Technology (IFE)		Chief Stakeholder Contact: Fred Martin Kaaby	
Internal Beneficiaries: 1. RISE, Sweden 2. BFKH, Hungary 3. CMI, Czechia 4. IMBiH, Bosnia and Herzegovina 5. PTB, Germany 6. TUBITAK, Türkiye 7. VSL, Netherlands 8. VTT, Finland	External Beneficiaries: 9. DTU, Denmark 10. GERG, Belgium 11. TFS, Germany	Unfunded Beneficiaries:	
Associated Partners: 12. NPL, United Kingdom			



Publishable Summary for 21NRM05 STASIS

Standardisation for safe implant scanning in MRI

Overview

Magnetic resonance imaging (MRI) is the gold standard for medical diagnostics with more than 40 million MRI scans performed in the European Union (EU) every year. Whereas this number is further increasing, scanning of patients with implants still poses a safety hazard. Even though international standards exist to address these risks, improvements are urgently needed and called for by implant manufacturers, Magnetic Resonance (MR) manufacturers and convenors of MR safety standards. This project aims at updating and improving the relevant standards providing clinicians with more confidence when scanning their patients, and implant and MRI systems manufacturers with novel methods to implement safety strategies for safe implant scanning.

Need

Medical implants are a 3 billion € market in the EU, with approximately 50 million citizens carrying one or more. Implants can be generally categorised into active implantable medical devices (AIMDs) or passive implants. Active implants (e.g. neurostimulators, cardiac pacemakers, implanted infusion pumps or internal defibrillators) require power to operate and have embedded electronic circuits that fulfill a specific function. Passive implants (e.g. hip or knee prostheses, stents, aneurysm clips or screws) do not require an external power source.

Due to comorbidity effects, 60- to 80-year-old have the highest probability of both needing an implant and an MRI. With an aging population, these numbers are likely to further increase. Metallic implants in a patient's body are a safety hazard in MRI, since interaction of the conductive device with the MR scanner's strong electromagnetic fields can result in dangerous tissue heating. Demonstrating compliance with MRI safety, in particular with respect to heating effects, is a challenging process with high product liability risks for implant manufacturers.

At present, regulators assess MRI compliance based on i) *in silico* test results, ii) knowledge of the expected electromagnetic fields in the patient body, and iii) history of the MR safety of similar products in service. But this is not based on quantified *in vivo* data, and it does not establish the risk to the patients. As a consequence, device manufacturers are unable to readily determine whether their device will be compliant prior to submission to the regulator. Therefore, future 'smart' implant technologies for medical and non-medical use are needed. 'Smart' AIMDs equipped with simple, small, and cost-effective sensors, could communicate with a parallel transmission (pTx) capable MRI scanner. It has been demonstrated that pTx is capable of steering radiofrequency (RF) electric fields away from the implant, thus substantially reducing hazardous tissue heating, still maintaining the imaging quality at a level comparable to the implant-free case. Additionally, because the EU's Medical Device Regulation (MDR) demands that medical implants and MRI scanners adhere to harmonised standards, improvements to such devices will only have a tangible impact once incorporated into standards.

Heating of bulky metallic passive implants due to MRI switched gradient fields demonstrated, in some cases, to exceed RF induced heating posing an often-unrecognised hazard for implant carriers. Some normative documents, e.g. ASTM F2182 ignore this effect completely, while others, e.g. ISO/TS 10974 are limited in

scope just to those implant categories where that effect is least relevant. Therefore, a dedicated methodology must be developed to address this issue.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: May 2024

At an international stakeholder workshop organised by the predecessor EMPIR project 17IND01 MIMAS, convenors and chief representatives for the three most relevant standards on implant safety in MRI (ASTM F2182, ISO/TS 10974, and IEC 60601-2-33) expressed the need for further work on a metrologically sound assessment of all uncertainties and risks associated with implant safety in MRI; development and documentation of standardisation-compatible test procedures; open-source hardware, design concepts and ideally prototypes of suitable testing hardware; as well as guidelines for *in vitro* testing of gradient-induced heating of medical implants.

Objectives

The overall objective of the project is to support standardisation for safety assessment of medical implants in MRI scanners. Medical implants can refer to passive implants (e.g., orthopaedic prostheses) or active implants (e.g., cardiac pacemakers or deep brain stimulators). Specific objectives are:

1. To develop, evaluate and explore the uncertainty (maximum tip E-field, SAR or temperature) of an implant safety concept in MRI comprised of sensor-equipped smart medical implants (e.g., pacemakers or neurostimulators) and pTx capable MRI scanners to assess and mitigate *in situ* RF induced implant heating. In addition, to formulate technical specifications for sensor-equipped smart medical implants and a communication interface between such implants and an MRI scanner.
2. To develop open-source reference hardware and traceable measurement procedures that allow testing of implants (mainly active) under pTx MR conditions. In addition, to develop, design and build a preliminary version of an open-source reference system of a pTx body coil and RF transmission hardware, suitable for offline implant testing by manufacturers and test houses.
3. To develop standardised measurement procedures for the interaction of bulky passive metallic implants with RF fields and alternating gradient coil magnetic fields in the kHz range. In addition, to provide guidelines and technical specifications for comprehensive *in vitro* testing of gradient-induced heating of such implants.
4. To contribute to the standards development work of ISO 10974, ASTM F2182 and IEC 60601-2-33 to ensure that project outputs are aligned with the needs of these bodies, communicated quickly to those developing the standards and to those who will use them (MRI and implant manufacturers, test houses) and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Objectives 1 and 2

Physical sensors on implants are not at all uncommon, e.g., they are used to determine the stimulation threshold of a pacemaker. However, their application to ensure patient safety in MRI certainly is. The concept of sensor-equipped smart medical implants in conjunction with pTx capable MRI scanners is a potentially disruptive approach to assess (via the implant sensor) and mitigate (via the scanner's pTx system) RF induced implant heating in MRI *in situ*. At present, only the implant is characterised by an assessment which is completely off-line (temperature and field measurements in homogeneous liquids or gels and numerical simulations of human voxel models). The proposed sensor-based assessment replaces most of the extensive off-line characterisation of the implant by a careful sensor calibration. Once this is done, the crucial question whether or not an MRI scan is safe needs no longer to be decided off-line, based on phantom measurements or some generic voxel models. It will be decided *in situ*, i.e., for the given patient, with a given implant, lying in a specific position in a given MRI scanner with a specific MR sequence to be run. More importantly, the responsibility for the scan is transferred: both the implant manufacturer and the scanner manufacturers assume the full responsibility (with well-defined and well separated roles), while the MR operator just gets a push-button solution.

Implant reference hardware with sensor-embedded hardware has been designed and used in first calibration measurements using external E-field and temperature sensors. A simulation setup has been generated and validated against field and temperature measurements. This simulation and testing environment allows calibrations of sensor-equipped implants and can be translated to investigate various clinical RF exposure scenarios. A wireless communication workflow has been established connecting implant reference hardware and a commercial 3T MRI scanner. Transmission speed, data rate and data volume were adjusted to reach on-the fly transmission of safety relevant information and use this information to suppress RF induced heating

at the implant tip. This setup was tested under varying conditions in realistic exposure settings. It was furthermore demonstrated that the impedance measurements of a commercial deep brain stimulator can be used to assess and mitigate RF induced heating, showcasing that the technology and methodology needed for a smart medical implant safety concept is within reach.

Objectives 3 and 4

Previous investigations demonstrated that in certain cases the gradient-induced heating of an implant during an MRI scan can be even more hazardous for the patient than RF induced heating. For active implants some guidance exists in the ISO/TS 10974 to test gradient coil (GC) heating of implants; however, this methodology needs further extensions. At the same time, the ASTM F2182 standard, which is widely adopted for safety testing of passive metallic implants, does not provide any guidance at all. Standardisation convenors have urged for more research to fill these critical gaps, and in response the project will develop a two-tiered testing approach. Test houses will be provided with validated and efficient procedures to assess gradient induced heating of implants. A standard draft for testing of gradient magnetic field induced heating on or near metallic implants will be developed and submitted to ASTM. In addition, the simultaneous exposure of implants to switched gradient and RF fields will be investigated extensively in numerical simulations to identify and inform the community about high-risk scenarios.

Comparison between ISO experiment and realistic exposure scenarios involving all the investigated implants showed that the first always leads to an overestimation of the peak temperature increase. This fully justifies the uptake of a Tier 2 approach optimised to improve the procedure proposed in the ISO/TS 10974 standard reducing the overestimation of the safety limits in case of orthopaedic implants.

An efficient procedure to compute the temperature increase induced on an implant by a homogeneous, harmonic magnetic field, arbitrarily oriented in space, has been devised. This procedure allowed to clearly identify the orientation of the specimens needed to perform the ISO experiments and to compute the so called “anisotropy coefficients” accounted for the definition of the new Tier 2 testing approach.

Several thermal experiments have been carried out both in an ad-hoc exposure system and in realistic gradient coils, with the main aim of validating the simulations and determine the uncertainties. On the basis of the obtained results, a Tier 2 approach has been proposed to reduce the degree of overestimation introduced by the ISO testing procedure. Human CAD models are used for performing a number of numerical simulations where each model is exposed to the electromagnetic field generated by the radiofrequency (RF) and gradient coils (GCs) during MR examinations. A numerical framework to combine the results has been set-up and will be used to perform thermal simulations combining the powers from RF and GC exposure. Project results have been presented and discussed at various working group meetings of relevant MR safety standards.

Outcomes and impact

The project produced seven scientific publications in peer-reviewed journals and >15 peer-reviewed abstracts in international conferences. The project results were very well received winning several awards at international meetings, they were highlighted by journal editors, figures were picked as cover art for high-impact journals, disseminated further in press releases and interviews with consortium members were published on the results of the project. Seven open-source repositories were published so far, containing hardware designs and code from the project facilitating reproducibility and impact for industry, academic institutions and other stakeholders.

Project results were also presented at standardization meetings, international and national conferences, stakeholder workshops, university lectures, educational training courses, exhibitions for policy makers and the broader public. Ongoing discussions with manufacturers and other stakeholders are currently targeting a transfer of these results into new products and improved standards to improve patient safety and clinical workflows in MRI.

Outcomes for industrial and other user communities

This project will directly support implant and MRI manufacturers as well as testing laboratories or regulatory bodies. Implant manufacturers are currently submitting applications for the approval of MRI safe or conditional safe implants, and the regulators are approving these applications according to the ISO/TS 10974 or the ASTM F2182 despite the recognised gaps. The project will close many of these methodological gaps and contribute to updated, improved and new standards. Development costs for the implant industry will be reduced and possibly overpriced costs for recalls or liability claims avoided.

The communication workflow for a novel safety concept developed on smart medical implants will furthermore dissolve the current stasis in safety and innovation around MR compatible implants and will speed up innovation both on implant and MR innovation side. The generic open-source implants and procedures produced, will enable simple validations of these concepts, and enable validation of product prototypes without the need to share proprietary information.

Discussions have been started with implant manufacturers, MR manufacturers, and the research community during international meetings, standardization meetings, and stakeholder workshops. Initial proof-of-concept implementations were successful, utilizing self-built hardware and methodology along with unmodified commercial implants. These results have been presented at peer-reviewed conferences and published in academic journals to pave the way for this novel implant safety concept. Additionally, several open-source repositories were created to share hardware designs and methodologies, enabling industry and academic institutions to reproduce, test and innovate.

Outcomes for the metrology and scientific communities

All measurement hardware (test artefacts and technical design files) and methodology in this project will be easily accessible and reproducible through open-source publications and maintenance. Several open-source software and open-source hardware repositories were already created and are regularly being updated. Participating NMIs as well as national and industry measurement laboratories across Europe will thus be enabled to provide the traceability for all measurements during the MRI safety assessment of an implant. This will also enable to pick up safety assessment methodologies developed in the project, to expand and extend them and to translate them to future normative work.

Outcomes for relevant standards

There is an intense standardisation effort on implant safety, including heating from RF and gradient coils, involving many standardisation bodies (ISO, CEN, ASTM, NEMA). The most far-reaching standardisation document, ISO/TS 10974, however, has many open questions that must be answered. As members of this consortium are on the standardisation group and have contributed significantly to the development of the Technical Specifications, the results of this project will directly benefit the development of the standard. Significant results of the project will be summarised and inserted into the ISO/IEC joint working group over the project timeline.

The consortium has also been equally involved in the major revision of IEC 60601-2-33, that also considers the special conditions of passive and active implants and multi-channel transmission. The consortium furthermore presented project results to this and other working groups around relevant standards on active and passive implants. Several scientific papers have been published and stakeholder workshops organized to present and discuss project results. As a result of the project a comprehensive standard testing procedure will be formulated and submitted as a work item to a current ASTM standard committee, such as ASTM F04.

Longer-term economic, social and environmental impacts

- Drive innovation, provide legal certainty, and improve market opportunities for implant manufacturers.
- Strengthen the position of MRI manufacturers as technology leaders in their fields.
- Provide better and safer access to MRI for implant carriers.
- Improved safety standards (ISO 10974, IEC 60601-2-33, ASTM F2182) and guidance documents.
- Implant manufacturers will benefit from faster development and market introduction of their innovative products
- MRI manufacturers will benefit by new applications for their innovative developments in parallel transmission technology.
- The mostly overlooked hazard due to gradient induced heating of metallic non-active implants will be finally addressed in the relevant standards.
- Overly conservative safety measures that limit imaging performance both for RF and gradient induced heating can be avoided leading to better image quality in the presence of implants, which is needed for diagnostic purposes.

- The healthcare systems in the EU will benefit from cost reduction by the proposed smart implants approach, i.e., shorter times for risk assessment and MR scan time reductions due to improved imaging performance in the presence of implants
- The work will facilitate the inclusion of implant MRI compatibility in future revisions of the EU Medical Device Regulations, enhancing the safety of EU citizens bearing implants.
- The applied dissemination of the project results as open-source hardware follows the recommendations towards the U.N: sustainable development goals (SDGS). International organisations and governments can increase their innovation capacity through open hardware, which can build innovation capacity in countries with low investments in science, technology and innovation, it enables new multi-stakeholder partnerships and collaborations between academia, civil society and the private sector, it makes science more transparent and participative, supporting global decentralised collaboration. In addition to that, international organisations can promote open hardware by incorporating it into their strategies, aligning incentives and raising awareness through education and training.

List of publications

Goren, T. et al (2023) 'Influence of patient head definition on induced E-fields during MR examination', *Magnetic Resonance in Medicine*, 91(2) p. 735-740. Available at <https://doi.org/10.1002/mrm.29894>

Petzold, J. et al (2023) 'Towards an integrated radiofrequency safety concept for implant carriers in MRI based on sensor-equipped implants and parallel transmission', *NMR in Biomedicine*. Available at <https://doi.org/10.1002/nbm.4900>

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Silemek, B. et al (2023) 'Wirelessly interfacing sensor-equipped implants and MR scanners for improved safety and imaging', *Magnetic Resonance in Medicine*. Available at <https://doi.org/10.1002/mrm.29818>

Winter, Lukas et al (2023) 'Open-source magnetic resonance imaging: Improving access, science, and education through global collaboration', *NMR in Biomedicine*. Available at <https://doi.org/10.1002/nbm.5052>

Zanovello, U. et al (2023) 'Efficient prediction of MRI gradient-induced heating for guiding safety testing of conductive implants', *Magnetic Resonance in Medicine*, 90 p. 2011-2018. Available at <https://doi.org/10.1002/mrm.29787>

Zilberti, L. et al (2023) 'Orthopedic implants affect the electric field induced by switching gradients in ', *Magnetic Resonance in Medicine*. Available at <https://doi.org/10.1002/mrm.29861>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 October 2022, 36 months
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Project website address: https://www.ptb.de/stasis/		
Chief Stakeholder Organisation: ISO TC150/SC6/JWG2		Chief Stakeholder Contact: Michael Steckner
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	4. DKFZ, Germany	
2. CMI, Czechia	5. MRC, Germany	
3. INRIM, Italy	6. STU BA, Slovakia	
Associated Partners: 7. ITIS, Switzerland		

Publishable Summary for 21NRM06 EMC-STD

Metrology for Emerging Electromagnetic Compatibility Standards

Overview

All electronic devices sold in the European Market are required to meet the essential criteria outlined in the European EMC Directive 2014/30/EU. Compliance with this directive is demonstrated through the use of standardized electromagnetic compatibility (EMC) measures. However, the rapid growth of radio services and cutting-edge technologies like Smart Grids, Internet of Things (IoT), and electromobility has created new scenarios where existing standards fall short in addressing interference issues effectively. Consequently, there is a need for validated and traceable methods to assess electromagnetic emissions in complex situations, including in-field testing of large and high-powered equipment (particularly covered by CISPR 37 & CISPR 11) and interference in wireless communications (mainly addressed by CISPR 16). This project's objective is to make substantial contributions to the enhancement of CISPR 37 and the revision of CISPR 11 and CISPR 16. This will be achieved through the development of new test methods for electromagnetic emissions in challenging environments, the implementation of fully traceable time-domain measurement techniques, the introduction of novel calibration techniques for receiver response to pulses, and the statistical analysis of interferences in compliance evaluations.

Need

All electronic devices sold in the European Market are obligated to meet the fundamental criteria outlined in the European EMC Directive 2014/30/EU. The customary procedure involves demonstrating adherence to harmonised standards by conducting EMC tests at specialised laboratories. Nonetheless, as novel scenarios of interference emerge due to the rise of radio services and cutting-edge technologies, like Smart Grids, IoT, electromobility, and sustainable energy applications, the existing standardised EMC testing methods are no longer sufficient or suitable. This concern has been underscored by both CENELEC TC 210 and CISPR, which are continually striving to establish updated and innovative EMC standards. Similarly, IEC is also addressing EMC issues at lower frequencies, with a current focus on interference below 150 kHz, particularly concerning smart energy meters.

A developing standard, CISPR 37 Ed. 1.0, aims to address the gaps left by CISPR 11, particularly regarding on-site testing outside established test sites. To facilitate the development of CISPR 37, the CISPR/CISB/WG7 was established, seeking assistance from universities and NMIs to create traceable electromagnetic emissions measurement techniques tailored for on-site evaluation of large-scale/high-power equipment (such as photovoltaic installations, electric road systems, and high-capacity electric vehicle charging stations).

As indicated by CISPR/CISA, there is a need for metrological research in applying time-domain electromagnetic interference (EMI) measurement techniques based on direct sampling methods. The standard defining characteristics and essential specifications of measuring receivers, CISPR 16-1-1, lacks clarity in terms of the metrological definition of the calibration method and the standard reference for ensuring the traceability of pulse response of detectors. A comprehensive waveform specification for receiver pulse calibration is imperative.

Furthermore, given the growing number of wirelessly connected devices due to the proliferation of IoT and the advent of 5G, the statistical analysis of interference and its correlation with communication quality metrics are of paramount importance. The APD measuring function can evaluate the degradation experienced by digital communication systems, but it requires modification in two key aspects: extension below 1 GHz and

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: May 2024

adjustment of the measurement bandwidth based on the characteristics of the communication channel. These adjustments should be incorporated into standards like CISPR 16-1-1 and CISPR 11. Similarly, a distinct calibration method for the APD measuring function of EMI receivers needs to be formulated to ensure the necessary traceability.

Objectives

The overall aim of the project is to support standardisation in electromagnetic compatibility (EMC) through the introduction of new, validated, and traceable emissions measurement methods for the revision of and forthcoming development of CISPR EMC standards.

1. To develop traceable electromagnetic emissions measurement methods optimised for in situ assessment of large-size/high-power equipment and to validate the proposed test procedures in harsh environments (e.g., factory premises and photovoltaic installations), which requires development and improvement of live impedance measurement methods in low (30 Hz – 150 kHz) and high (150 kHz – 30 MHz) frequency ranges for conducted emission testing with a target uncertainty of 6 dB. This also includes the characterisation of influence factors such as non-stationary interferences and sources of background noise, correcting the impact of transient interference, and defining a measurement protocol for selecting adequate antenna location, height, and polarisation, and other relevant parameters for the radiated emissions test setup. A report on the methods will be submitted to CISPR/CIS/B/WG7 to support the development of the forthcoming CISPR 37.
2. To provide metrological evidence of the validity of time-domain electromagnetic interference (EMI) measurement systems, based on direct sampling techniques, and to define standardisable conditions at which the usage of oscilloscopes/baseband digitisers is acceptable or preferred in comparison to measuring receivers based on frequency sweep or stepped scan techniques. The estimation of the uncertainty in time-domain EMI measurement systems will be addressed. A report recommending an amendment of Annex B and Annex C of the current CISPR 16-1-1 standard will be submitted to CISPR/CIS/A/WG1 & WG2.
3. To improve the standard calibration method for the response to pulses of measuring receivers through a complete waveform specification of the calibration pulse generator. To develop alternative reference waveforms with well-defined mathematical description and spectral properties to include in standards as a means of validating the weighting function of the detectors, thus reducing the uncertainty of the receiver's response to pulses calibration to 0.2 dB. A report on the proposed calibration methods for the response to pulses of measuring receivers will be submitted to CISPR/CIS/A/WG1 & WG2 to support amendment of CISPR 16-1-1.
4. To redefine the standard amplitude probability distribution (APD) measuring function in EMI measuring receivers as part of the emissions compliance assessment based on the communication quality metrics. To define the criterion for establishing emissions limits based on APD measurements making it part of the emission compliance assessment. A report on the redefined APD measuring function will be submitted to CISPR/CIS/A/WG1 & WG2 and CISPR/CIS/B/WG1 to support amendment of CISPR 16-1-1 and CISPR 11 respectively.
5. To contribute to the standards development work of the technical committees CISPR/CIS/A/WG1 & WG2 (supporting revision of CISPR 16-1-1), CISPR/CIS/B/WG1 (supporting revision of CISPR 11), and CISPR/CIS/B/WG7 (supporting development of new CISPR 37) to ensure that the outputs of the project are aligned with their needs. To communicate quickly to those developing the standards and to those who will use them (test laboratories and manufacturers related to IoT, E-mobility, and technologies), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Development of emission test methods for harsh environments (Objective 1)

A novel conducted emission measurement method utilising the live mains impedance measurement in the 30 Hz – 2 kHz frequency range has been developed. It has been proven that there is a precise correlation between the mains impedance and the measured conducted emission current. Further investigations for the

2 kHz – 150 kHz range is continuing. In order to complete the whole frequency range up to 30 MHz, time-domain techniques and phase information will also be included to improve accuracy and uncertainty. After the method has been repeated in different laboratories and consistent results have been obtained in the comparison measurements, the consortium will perform joint in-situ measurements for high-power/physically large, atypical equipment (e.g. photovoltaic systems and EV high power chargers). Companies from different countries such as Türkiye, Spain and Italy are interested but the final measurement locations will be agreed in consultation with the Chief-stakeholder.

A compact impedance measurement device has been constructed. It has been designed to measure the live impedance of a low voltage AC (230 V) grid and vehicle DC networks. A measurement campaign has been organised between TUBITAK, UNIGE and SIQ at the laboratory of SIQ for comparison of the measurement results of the device which will serve as an essential part of the novel conducted emission measurement method. The consortium plan to present the device and its result at the EMC Europe 2024 Conference, a paper “A portable VNA-based system for grid impedance measurements” has been submitted to the conference and conditionally accepted. Progress for reply to reviewers’ comments & questions in going on.

Work has been done to improve the uncertainty calculation of conducted emission measurements. Uncertainty contribution arising from AMNs (Artificial Mains Network) is of particular concern among EMC experts. Since there is not a comprehensive guide for the uncertainty contribution of LISNs to the uncertainty budget, a free software tool has been developed. A paper titled “Investigation of AMN Impedance Uncertainty Contribution in Conducted Emission Tests” has been published in IEEE EMC Magazine. The tool is free to download from the project website and on [Zenodo](#).

For radiated emission testing, methods proposed by the draft standard CISPR 37 have been investigated, including not only electric field emissions (30 MHz – 1 GHz), but also magnetic field emissions (9 kHz – 30 MHz). The efficiency of time domain measurement has been demonstrated with 6 samples, in industry. Those were; a pallet washing machine (industrial machines), an airplane passenger boarding bridge (transportation industry), photovoltaic system inverter and the system itself (renewable energy industry), personal computer (IT industry) and an electric motor equipped with a variable speed driver. Also, multi-resolution bandwidth analysis, allows unmasking overlapped Equipment Under Test (EUT) and ambient noise frequency components at the CISPR resolution bandwidth (RBW). Moreover, the excellent performance and practical advantages of oscilloscope-based measuring receiver implementations has been confirmed through representative use cases, including synchronous multi-channel setups. The measurement speed and efficiency for characterising FFT-based receivers allow real-time analysis independently of the selected RBW, therefore, they are ideal for analysing emissions in dynamic and time-sensitive environments. Another key advantage, from now on, is the possibility to perform off-site reprocessing, maintaining the efficiency of the measurements during the campaign and allowing the detailed analysis of each case separately. Furthermore, time-gating is employed to remove sporadic and transient events from the final results. As the last improvement, time decomposition to exclude stationary ambient noise between impulsive events generated by the EUT.

Specifying time-domain interference measuring receivers in EMC standards (Objective 2)

Two experimental campaigns have been carried out for benchmarking measuring receivers for conducted and radiated emissions. Low-cost USB digitiser, a high-performance bench-top oscilloscope and several high-end fully compliant EMI receivers have been used in that process. In one experiment, simulated signals were applied to receivers in order to see real-life scenarios. More recently, the comparison was extended using off-the-shelf switched mode DC/DC power converters as sources of noise. Benchmark results show that time-domain measurements with oscilloscopes are highly promising. Given the excellent quality of the results obtained, it is recommended to take advantage of the wide availability of oscilloscopes for doing EMI checks, for supporting the electronic design teams at pre-compliance stages, and streamline compliance evaluation. A complete throughout analysis has been made of the parameters of spectral estimation algorithms and their influence in the measurement error has been carried out through simulations and experiments. Optimal or close to optimal settings for the windowing function, overlapping factor and frequency interpolation have been determined. Further investigations on time-domain techniques will continue in order to obtain a repeatable and reliable measurement method especially for the assessment of challenging in-situ measurement methods thereby ensuring that the method can be implemented in CISPR 16-1-1 and in CISPR 37 standards.

Methods for calibration of measuring receivers (Objective 3).

Several methods for the calibration of baseband pulse generators were reviewed using instrumentation available at CMI ('Fourier transform of time-domain pulse waveform', 'Intermediate-frequency measurement method', 'Measurement of pulse amplitude and duration' and 'Measurement of one spectrum line amplitude'). The Fourier transform method was determined as the most suitable and easy-to-use. A review of the CISPR 16-1-1 standard specifications was completed. Firstly, no waveform characteristics are given for the reference pulses. In particular, the peak amplitude of the pulse that would be required, its rise time, or its mean duration are not given in the corresponding standard. That is a key omission that should be fixed. Secondly, from the standard definition, the typically used calibration pulses won't meet the cut-off frequency requirement. The corresponding theoretical values have been calculated and are rather extreme, particularly for the amplitude. There is no strong justification for the need to use such pulses for calibration purposes. A document summarising these two main points are in preparation progress.

CMI and GUM calibrated their base-band pulse generators using various methods and the measurement uncertainty has been evaluated for each method based on available equipment. RISE calibrated their pulse-modulated RF signal generator. A draft recommendation document was started which will include practical hints for calibration of various pulse generators used for calibration of measuring receivers. The document aims to recommend changes of particular CISPR 16-1-1 clauses with respect to pulse generator calibration methods and their suitability for commercial calibration laboratories.

Work on characterising the alternative pulse waveform for the calibration of EMI receivers is ongoing. The main target of which is to generate pulse waveforms by less complicated hardware (i.e. arbitrary waveform generator).

The APD interference detector in emissions compliance assessment (Objective 4)

The APD measuring function defined in CISPR 16-1-1 has been reviewed and a new definition has been proposed. This proposal gives a more flexible and general definition for the APD measuring function, offering relevant advantages compared to the standard method. The new definition avoids unsubstantiated specifications or conditions currently identified in the standard APD measuring function. Also, the proposed method aligns with the core purpose of APD since it considers and handles the measured amplitude as a random variable. Therefore, the new approach allows significant APD estimations to be obtained using smaller samples, that is, in less measurement time. Under the same conditions, the algorithm delivers low probability levels that the standard procedure fails to detect. This is possible because of the application of Kernel Density Estimation instead of the histogram method. APD measurements have been carried out below and above 1 GHz using either an oscilloscope, software defined radio devices and FFT-based measuring receivers. The comparison indicates a good agreement between all them under additive white Gaussian noise, pulsed and continuous wave conditions. APD analysis shows that some disturbances can be underestimated by quasi-peak detection methods. In the following months, a calibration procedure for the APD measuring function is envisaged along with the corresponding uncertainty budget.

Outcomes and impact

A stakeholder committee of 10 members (including standard committee members and company representatives) was created at the start of the project and there are currently 12 members. The first stakeholder workshop was held alongside the CISPR 37 draft standard committee meeting in April 2023, Barcelona. The consortium informed stakeholders about the project and received their suggestions with regards to the latest targeted standardisation projects.

TUBITAK, GUM, EMC-BCN, CMI and UNIGE have attended their national EMC committees during the first 18 months to inform them about the project.

On March 12th, there was an online meeting with the CISPR chair, when the project, its progress made so far and its potential contributions to CISPR standards were promoted.

Partners attended the EMC Europe 2023 conference in Poland and the Photonics and Electromagnetics Research Symposium 2023 (PIERS). 5 papers have been presented at these conferences and 2 journal articles have been published in IEEE Open Journal of Instrumentation and Measurement and IEEE EMC Magazine. The consortium hosted a special session successfully at the EMC Europe Symposium 2023 titled

as “In-situ Electromagnetic Emissions Measurements: Challenges and Solutions for Assessing Atypical Equipment”. 8 papers from different authors were presented in the special session.

The consortium has been active in several standardisation committee meetings either face-to-face or online. In addition, they have been participating in in-situ measurement campaigns with several companies utilising their cutting-edge time-domain measurement methods and specialised hardware and software as well as in training activities in doctoral networks and in companies.

A **project website** has been created and is regularly being updated by CMI with information such as news, events, training material, project reports, papers published by the participants, project meetings and the project’s promotional material including its publishable summary and e-newsletters.

Outcomes for industrial and other user communities

TUBITAK successfully completed conducted emission by live impedance measurement method in the 30 Hz – 10 kHz frequency range. TUBITAK also completed the construction of the compact impedance measurement device. This device allows impedance measurement in networks. A fixture for live grid impedance measurement in 2 kHz – 30 MHz frequency range is being studied by UNIGE. After verification of live grid impedance measurements, TUBITAK will start to develop the in-situ conducted emission method in the 2 kHz – 30 MHz frequency range.

The time domain method was taken up by EMC-BCN in several campaigns, one of which is with a representative (the chief stakeholder) from Fuji Electric Europe for the measurements in large scale photovoltaic energy systems in Magdeburg, Germany. EMC-BCN also performed many measurements from different atypical devices (i.e. palette washing machine, a passenger boarding bridge for airplane, automotive equipment, space applications) of various manufacturers. EMC-BCN performed time-domain emission measurements in Fronius Solar Inverters premises. More time-domain measurements will be implemented during the lifetime of the project. This method allows industry to acquire short duration/transient interference and worst-case emission measurements in harsh environments in real time. As opposed to conventional frequency-domain instrumentation like EMI receivers, this allows industry to achieve a drastic reduction of measurement time, from hours to less than a minute.

The software solutions will be taken up by TUBITAK and EMC BCN and provided to end users (e.g., other EMC laboratories and manufacturers) who need onsite EMC testing for their products. This will provide accurate and practical on-site test opportunities for them to validate their products as per the relevant EMC standards such as CISPR37.

The instrumentation will be taken up by TUBITAK, RISE, EMC BCN, UNIGE and incorporated into their measurement and consultancy services and offered as a service to customers who need on-site EMC testing for their products and require verification and comparison tests for their EMC test systems. This will allow industry to validate their products which are not suitable for transferring to EMC laboratories due to physical and power constraints. Participants will also consider the possibility of transforming this development into a commercially available product it to third parties such as EMC test laboratories, either sold or as part of a verification service.

In addition, the test methods and assessment methodologies based on APD detectors will be taken up by CISPR/CISA committees to facilitate more reliable measurement procedures for radiated electromagnetic emissions at real sites, backed up by the quantification of disturbance to telecommunication systems. This will allow manufacturers (e.g., railways that feature large moving sources, potentially disturbing deployed telecommunication systems with signalling functions) to demonstrate the compliance and safety assessment in a more straightforward way. This will facilitate reduced duration of safety assessment and demonstration of compliance (usually blocking the permit to operate). Additionally, the broader use of APD as an interference detector will benefit industry because it mitigates the risk of over/under testing their products, which inevitably happens today due to the utilisation of non-optimum weighting detectors for emissions assessments.

Outcomes for the metrology and scientific communities

EMC-BCN organised training for the ETERNITY Doctoral Network in Barcelona on 6th July, 2023 during a network-wide event of ETERNITY, with the participation of 12 PhD candidates and 15 researchers and representatives of the ETERNITY consortium.

CMI and GUM calibrated their base-band pulse generators using various methods and the measurement uncertainty has been evaluated for each method based on available equipment. RISE calibrated their pulse-modulated RF signal generator. A draft recommendation document was started which will include practical hints for calibration of various pulse generators used for calibration of measuring receivers. The document aims to recommend changes of particular CISPR 16-1-1 clauses with respect to pulse generator calibration methods and their suitability for commercial calibration laboratories.

The joint interdisciplinary research of emissions measurements in harsh environments and the further development of APD as an interference detector will improve scientific understanding in this technical field. New research lines are expected to be generated. For example, doctoral Networks (Marie Skłodowska-Curie Actions) addressing EMC challenges in innovative applications (e.g., ETERNITY for EMC in medical equipment, PETER for electromagnetic risks management, ETOPIA for power applications). Technical training for ETERNITY Doctoral Network has been accomplished. This training reached to approximately 40 researchers from academia. By this training, researchers were informed about advantages and aspects of time-domain measurement. It is envisaged that spreading time-domain knowledge will make faster integration of the method in relevant standards. Besides, this training will provide awareness on in-situ measurements which are very useful for large medical devices those interesting the ETERNITY network.

Outcomes for relevant standards

The project will contribute to the standards development work of the technical committees CISPR/CIS/A/WG1 & WG2 (supporting revision of CISPR 16-1-1), CISPR/CIS/B/WG1 (supporting revision of CISPR 11), and CISPR/CIS/B/WG7 (supporting development of new CISPR 37) to ensure that the outputs of the project are aligned with their needs.

As mentioned previously, the consortium has attended several standardisation working group meetings such as online meetings of CISPR 37 draft standard, as well as IEC 62920, CISPR 11 and CISPR 16-1-1 meetings and IEC-TC 82/WG 6, TC 219 and CISPR A JWG meetings. Project partners informed several standardisation experts on various platforms. Information about the project has been shared with the StandICT.eu 2023 initiative partners. Since StandICT directly focuses on standardisation it has a wide impact on the community.

Since the chief stakeholder is already active in various standardisation projects (CISPR 37, IEC 62920,) joint measurement activities performed by EMC-BCN and Fuji Electric is directly contributing in increasing the awareness of standardisation committees.

The consortium also presented the EMC-STD project in a general meeting of the Turkish EMC mirror technical committee. This presentation reached Turkey's largest electronic equipment manufacturers.

It is planned to draft a recommendation on calibration of pulse generators for CISPR 16-1-1 and then, send it to the CISPR\CIS\A and CISPR\CIS\B committees for consideration.

Longer-term economic, social and environmental impacts

One sector that will considerably benefit from project outcomes is the industrial, scientific and medical (ISM) one because the most prominent target standards in the scope of the project is CISPR 37. Like CISPR 11 that was partially used for years as a reference standard for large equipment, CISPR 37 is expected to be effective on renewables and wireless power transfer, their integration in microgrids and power distribution infrastructure, railways, automotive and large machine manufacturers. Uptake of novel methods proposed by this project has partially started but the wider impact is naturally a time-consuming process.

In particular, as declared by the European Commission (EC), the objective for solar energy is to establish Photovoltaic (PV) systems as a clean, competitive and sustainable energy technology. Therefore, the improvement and production of new EMC standards for atypical equipment can improve the certification of PV installations and consequently achieve the objective of implementing solar energy, which will benefit economically the end-users, to reduce their energy consumption and produce their own clean energy, and the companies which provide the PV infrastructure.

The EC also supports European industry in the move to a low-carbon economy and improves the energy efficiency of products through eco-design legislation. This is strictly related to the energy industries like PV

and green transport. The new EMC standards will contribute, from an EMC point of view to evaluation of all the novel electric engines and energy-efficient functional modes like regenerative braking that is employed by Electrical Vehicle (EV) such as trains, metros and e-buses. Some EV charger manufacturers from Europe (one in Spain, one in Turkey) declared their interests in the project during workshops. Particularly, EV high-power DC chargers are a concern of power distribution installations.

Moreover, citizens can have direct social benefits from the energy and transport industries. A sustainable mobility is beneficial for the free movement around the European Union (EU), and according to the European Economic and Social Committee (EESC), these movers represent a poll for innovation, creativity, and willingness to work hard. The use of renewable energy technologies has a direct positive impact on the health of the European citizens. Therefore, the validation and procedures developed with the actual official standards in lieu of non-standard methods will allow speeding up the certification and the confidence in being compliant with the European Directives. In addition, taking advantage in the improvement of standardised, repeatable and traceable methods for in situ EMC testing of large-size/high-power equipment, reliable test results for a wide variety of locations will be obtained. Thus, manufacturers, conformity assessment bodies and consumers can benefit from reliable and faster compliance processes with the European EMC Directive 2014/30/EU and this presents significant opportunities for free movement of goods in European Single Market, promising potential cost savings and time.

List of publications

- ÇAKIR, Soydan et al (2023) 'Improvement in Low Frequency Emission Test Method by Live Impedance Measurement', International Symposium and Exhibition on Electromagnetic Compatibility. Available at <https://zenodo.org/records/8383197>
- Azpúrua, M.A. et al (2023) 'Measuring Receiver Benchmark for Conducted and Radiated Emissions Testing in Space Applications', 2023 International Symposium and Exhibition on Electromagnetic Compatibility. Available at <https://doi.org/10.5281/zenodo.8375139>
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- Solé-Lloveras, J. et al (2023) 'Strategies Using Time-Domain Measurements for Radiated Emissions Testing in Harsh Environments', IEEE Open Journal of Instrumentation and Measurement, 2. Available at <https://doi.org/10.1109/OJIM.2023.3303950>
- Solé-Lloveras, J. et al (2024) 'Evaluation of Spectral Estimation Parameters for Direct Sampling FFT-Based Measuring Receivers', IEEE Open Journal of Signal Processing, 5 p. 588-598. Available at <https://doi.org/10.1109/OJSP.2024.3389825>
- Solé-Lloveras, Jordi et al (2023) 'Efficient In situ Assessment of Radiated Emissions using Time-Domain Measurements', 2023 International Symposium on Electromagnetic Compatibility, 1(1), p. 1-6. Available at <https://doi.org/10.5281/zenodo.8375102>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
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Chief Stakeholder Organisation: Fuji Electric Europe GmbH		Chief Stakeholder Contact: Yasutoshi Yoshioka
Internal Beneficiaries: 1. TUBITAK, Türkiye 2. CMI, Czechia 3. GUM, Poland 4. INTA, Spain 5. RISE, Sweden 6. SIQ, Slovenia	External Beneficiaries: 7. EMC-BCN, Spain 8. UNIGE, Italy 9. UTwente, Netherlands	Unfunded Beneficiaries: n/a



Publishable Summary for 22DIT01 ViDiT Trustworthy virtual experiments and digital twins

Overview

The use of virtual experiments (VEs) and digital twins (DTs) in metrological applications (e.g. coordinate measuring machines (CMM), tilted wave interferometer (TWI), flow measurement (FLOW), nanoindentation, 3D robotic measurement, electrical measurement) requires uncertainty evaluation methods, as well as reliable validation procedures, to make them fit, e.g. as substitutes or extensions, to certified measurement devices. This project will develop these methods and procedures to ensure the reliability and trustworthiness of VEs and DTs in metrology. In addition, this will enable the traceability of modern measurement systems and it will boost and strengthen the European lead in this field. To facilitate the uptake of the developed methods by NMIs/DIs and industrial stakeholders, three good practice guides (GPGs) will be written, and the applicability of the methods will be demonstrated in twelve case studies covering the aforementioned industrial metrology applications.

Need

VEs and DTs are key enabling technologies to achieve and realise European strategic policies devoted to sustainability and digitalisation within the complex framework of Industry 4.0 and the European Green Deal. VEs and DTs are both simulation models that accurately replicate physical systems and characteristics in a virtual environment. DTs further include dynamic updates of the virtual model according to the observed state of its real counterpart. Hence, they consist of two parts, a Physical-to-Virtual (P2V) connection that models the considered system and a Virtual-to-Physical (V2P) connection that implements prevention and control strategies to achieve the target accuracy in the physical system.

VEs, in combination with Monte Carlo simulation methods, are used for evaluating measurement uncertainties. However, the outputs of these approaches generally differ from an uncertainty evaluation that is compliant with the “Guide to the expression of Uncertainty in Measurement” (JCGM:GUM). Such a JCGM:GUM-compliant uncertainty evaluation is needed to facilitate the use of VEs in traceable measurement chains and to ensure trust in the stated uncertainties.

For DTs, in addition to this, time-dependent influences need to be considered. Hence, DTs need to be updated with data from actual measurements that are collected in real-time, and the evaluation of measurement uncertainty needs to be adapted accordingly to be compliant with the JCGM:GUM.

To trust the outcomes of VEs and DTs, a reliable validation procedure needs to be developed. Differences between calibrated standards (or measurement data obtained with calibrated instruments) and the corresponding data from the virtual counterpart need to be analysed and quantified to make VEs and DTs fit for use in metrology, e.g. as substitutes or extensions to certified measurement devices.

To ensure the uptake of the developed mathematical and statistical methods and procedures by industry, their applicability needs to be demonstrated, using case studies that cover several metrological applications. These case studies need to be defined and planned in close collaboration with industrial participants to ensure the effective uptake of the proposed methods in industrial setups.

Report Status:
PU – Public, fully open

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European Partnership Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: February 2024

Uncertainty evaluation and validation of VEs and DTs are essential parts of the strategic research agenda of the European Metrology Network (EMN) MATHMET. This research agenda is based on a survey of European NMIs and stakeholder consultations that identified virtual metrology as one of their priorities in the field of mathematics and statistics for metrology. This emphasises the need for this project.

Objectives

The overall objective of this project is to develop methods and tools that will ensure the reliability and trustworthiness of VEs and DTs in metrology in order to support digital transformation within Industry 4.0 and the European Green Deal.

The specific objectives of the project are:

1. To develop methods for evaluating the uncertainty associated with real measurements for three different applications (CMM, TWI, FLOW) by using the results from corresponding VEs in line with the current state-of-the-art for uncertainty evaluation, such as Bayesian or Monte Carlo approaches or documented in the JCGM:GUM. An open access software repository including the implementation of the methods, and a FAIR data set developed for the uncertainty evaluation of VEs, will be provided.
2. To develop methods for uncertainty quantification for DTs representing complex measurement processes and mechanisms for four different applications (nanoindentation, NanoCyl, 3D robotic measurement, electrical measurement), in each case including the effect of dynamic influences on the digital model such as thermal drift or vibrations. The model will be updated based upon data obtained during the project's lifetime. The open access software repository created in objective 1 will be extended by including the methods, and a FAIR data set, developed for the uncertainty evaluation of DTs.
3. To develop approaches for the validation of VEs and DTs for all applications of objectives 1 and 2, using statistical procedures for the assessment of differences between calibrated standards and corresponding data from their virtual counterpart. Methods include accounting for errors, specifically for computationally expensive systems, where surrogate models need to be used.
4. To demonstrate the practical applicability of the developed methods, using twelve different case studies covering six different metrological applications (coordinate measurement, optical form measurement, flow measurement, nanoindentation, 3D robotic measurement, electrical measurement). Guidance will be documented on how to employ the methods in other cases and reports will be drafted in collaboration with industrial participants and stakeholders and disseminated within e.g. European industry, Consultative Committee for Length (CCL), EURAMET TC Length (TC-L) and ISO communities.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, accredited laboratories, material testing laboratories, calibration laboratories), standards developing organisations (ISO, IEC) and end users (advanced manufacturing, personalised health care and urban planning).

Progress beyond the state of the art and results

As a VE usually produces virtual data rather than virtual values for the measurand, the uncertainty evaluation methods described in the JCGM:GUM cannot be directly applied and extra steps have to be taken to obtain a JCGM:GUM-compliant uncertainty estimate. Recently, a JCGM:GUM-compliant uncertainty evaluation has been reached for linear models in an automatic way by using the output of a VE. However, no procedure exists to derive the uncertainties for the result of a measurement, by automatically using virtual data when the model for the measurand is nonlinear. One objective of this project is to progress beyond the state of the art by developing such an approach. This will allow an automated uncertainty evaluation for general models using the outcome of a VE.

To this end, a literature review of state-of-the-art methods for uncertainty evaluation methods involving VEs and real measurement data has been performed. This review also establishes a vocabulary and mathematically concise description of VEs in terms of input-output relations. Subsequently, different classes of uncertainty evaluation methods were identified. In particular, the review distinguished between Linear Propagation of Uncertainty (LPU) methods, Propagation of Distribution (PoD) methods and Bayesian

approaches for uncertainty evaluation. In the next step, requirements, constraints, and challenges were identified for each method. Currently, an assessment of JCGM:GUM-compliance for the methods identified is being performed. For such an assessment, a precise and practical definition of the term JCGM:GUM-compliance will be required in the context of this project and practical guidelines will be developed. (Objective 1)

Very few examples of DTs are reported in the literature for measurement instruments or measurement processes, and there is even less literature on the uncertainty evaluation of DTs. Currently, available methods for uncertainty evaluation often neglect the coupling of a DT with its different parts, especially those linked to the control and the V2P connection. Moreover, a rigorous definition and evaluation of the metrological characteristics of the DT are missing. This project will progress beyond the state of the art by delivering different methods to evaluate the uncertainty of DTs for several measurement processes, for which JCGM:GUM-compliance will be analysed and reported. Additionally, the coupling with the modelling, and the control feedback deployment strategies, will be included in the uncertainty evaluation.

In the first nine months of the project, an extensive literature review has been performed to identify main applications and examples of measurement instrument DTs and corresponding uncertainty evaluation methods. A definition of DT was developed that is coherent with the recently published standard (ISO 23247:2021) and with the definition of VE. Accordingly, a DT consists of a physical asset and a virtual asset twinned by means of a bi-directional connection, i.e. the physical-to-virtual (P2V) and the virtual-to-physical (V2P) twinning. The former aims at updating the virtual asset and the latter to control the physical part. The definition identifies the DT as *a simulation model that accurately replicates physical systems in a virtual environment and includes dynamic updates of the virtual model according to the observed state of its real counterpart to achieve a physical control of the latter, wherein the virtual asset is a time-varying VE*. The literature review showed that, in the implementations of DTs, the bi-direction twinning is often disregarded. Towards meeting Objective 2, the main sources of uncertainty have been identified, namely due to diagnosis (sensors and P2V connection), prognosis (the virtual asset prediction) and epistemic (modelling) errors. Similarly, the main influence factors, namely sensor traceability, task-based influence factors, and environmental contributions, and methods to evaluate metrological characteristics, i.e. accuracy (by calibration on reference artefacts), precision/uncertainty and traceability, have been identified. In particular, methods to establish traceability have been identified, i.e. by calibrating sensors, actuators and characterising virtual asset modelling performances. Furthermore, criticalities in the propagation of uncertainty in the DT and its different parts, i.e. the physical and virtual assets, have been highlighted depending on the control strategies and the available sensors. Specifically, control strategies might be implemented depending or not on the current state and relying on sole proprioceptive sensors or leveraging data fusion through exteroceptive sensors. Theoretical propagation of contributions according to the law of uncertainty propagation has shown that the only methods that avoid an increase in the uncertainty in the state estimation are those relying on data fusion. Different applications are being developed to demonstrate the applicability of the uncertainty quantification methods, and the main parameters have been selected. (Objective 2)

Currently, there are no general guidelines for the validation of VEs/DTs. This project will progress beyond the state of the art by developing these guidelines with a special focus on their applicability to metrology. The validation will include both the measurement estimate obtained by the VE/DT, as well as the uncertainty associated to it. Knowledge and experience from existing applications of VEs in metrology (e.g. virtual coordinate measuring machine (VCMM)) will be applied in other applications that are new to the adoption of VEs/DTs (e.g. nanoindentation). Attention will be given to the broad applicability of the validation guidelines and also to non-standard measurements, e.g. measurements of freeform artefacts. Surrogate modelling will also be investigated as it has the potential to replace the VE/DT in online applications. A literature review of available methods for surrogate modelling has been performed. (Objective 3)

The uncertainty evaluation methods developed for VEs and DTs will be applied in twelve case studies covering different metrological applications. Where appropriate, existing software tools will be extended based on the expected results. For other applications, new environments will be created, such as DTs for a commercial nanoindentation platform or a traceable commercial robotic 3D scanning system. Guidance will be given on the practical applicability of the developed uncertainty evaluation methods when applied to industrial case studies. The reports will be drafted in close collaboration with the industrial participants and stakeholders. The results will be disseminated within the relevant European industry as identified by the EMNs AdvanceManu

and MATHMET, as well as by the consultative committees of the CIPM (e.g. CCL), EURAMET technical committees (e.g. TC-L) and ISO communities. (Objective 4)

Outcomes and impact

In the first nine months of the project, a Stakeholder Committee has been established consisting of 17 members so far. Furthermore, a meeting with a potential collaborator was held. A project webpage (vidit.ptb.de) has been created and is regularly updated with news about the project's first results and activities of the consortium. Furthermore, key information about the project has been summarised in a project flyer, a project poster, a press statement, and a first e-newsletter. These documents have been distributed at different occasions (e.g. during conferences and workshops or via the e-mail lists of *Metrology News* and the EMN MATHMET) and they are all available for download on the project webpage. News about the project is also distributed via LinkedIn, where a group for the ViDiT project has been created. First results and an overview of the aims of the project have been presented at several conferences and workshops (e.g. MSMM 2023, ENBIS 2023, 3DMC, etc.). A first peer-reviewed paper has been published. The consortium has informed JCGM WG1 about the start of the project and is in close contact with the EMN MATHMET.

Outcomes for industrial and other user communities

The outcomes of this project will include the provision of methods for the JCGM:GUM-compliant uncertainty evaluation of VEs and DTs, as well as procedures for their validation. Furthermore, the newly developed approaches will be applied to a variety of industrially relevant test cases. These methods, procedures and case studies will enable the industry and users of VEs and DTs to e.g. optimise meter design or to improve the efficiency of welding processes. This will provide the basis for gaining traceability in several metrological applications, where VEs/DTs are employed (e.g. asphere and freeform metrology, nanoscale mechanical characterisation, the quality control of welded parts). This will lead to a reduction in the production time as well as to parts being manufactured with better surface quality.

Industrial stakeholders will be involved in defining case studies to ensure the transferability of the developed methods and procedures for uncertainty evaluation and validation in industrial setups. First meetings with stakeholders took place within the first nine months of the project. The GPGs that will be written in this project will be disseminated to industrial stakeholders to further support the uptake of the developed methods in these and other fields of application. Additionally, representatives of industry (both manufacturers and users) will be invited to a workshop on uncertainty evaluation for VEs and DTs, which will be organised and held by the project. Members of the consortium participated in seminars and workshops to present the project and its impact on industrial applications, e.g., in the field of precision engineering and quality control.

Outcomes for the metrology and scientific communities

The outcomes of this project will provide a common understanding among European NMIs/DIs on how to make VEs and DTs fit for use in metrological applications. The methods for assessing the uncertainty will be summarised and published in GPGs so that they can be easily adapted by the metrological and scientific communities. Up to now, one research paper has been published in *Measurement*. By the end of the project, more results will be published in high impact peer reviewed journals, and as part of the knowledge transfer, a workshop on uncertainty evaluation for VEs and DTs, will be organised and held, to which representatives of academia and NMIs will be invited. Results will be disseminated to the EMNs AdvanceManu and MATHMET as well as to the International Academy for Production Engineering (CIRP), which will make them accessible to a wider audience including stakeholders from all these networks. Contact with the EMN MATHMET has already been established and its members and stakeholders have been informed about the start of the ViDiT project. Five presentations were delivered to the metrology and scientific community at MATHMET and ENBIS conferences and workshops. The collaboration of European NMIs and DIs in this project will increase their visibility and authority in drafting common regulations and guidelines. This will improve the competitiveness of the European economy and it will lead to a more intense international cooperation.

Furthermore, the project's results will provide high performance and robust methods that have the potential to be used in different applications, for example freeform optical surface measurements. The optical scientific community will be able to make use of these advancements and benefits in their research, e.g. with regard to the need for highly accurate complex optical systems in research fields such as lithography (e.g. extreme ultraviolet lithography), synchrotron, astronomy, ophthalmic, medical devices and many more. The benefits

will also be valid for the scientific communities that are involved in electrical measurements, flow measurements, nanoindentation measurements, etc.

Outcomes for relevant standards

The consortium will promote the results and outcomes of this project within the standardisation community and will provide input into the standardisation process. The participants of the project are active in the JCGM WG1, which has responsibility for the JCGM:GUM and its supplements. These documents mark the de facto standard for uncertainty evaluation in metrology and are used worldwide at all levels of the measurement chain, from NMIs to industry. Furthermore, the results of this project will be disseminated to DIN, ISO and CEN working groups. For ISO, the relevant standards that are in preparation/revision will be identified, and the work on these standards will be suggested to the appropriate working groups or committees. The participants will also present the outputs of the project to College International pour la Recherche en Productique (CIRP), EURAMET TC Length (TC-L), IMEKO, EURAMET and other networks, where they are active. All these activities will ensure the uptake of the project's outcomes by the metrological community.

Longer-term economic, social and environmental impacts

The improved capabilities at NMIs and DIs, which will be provided by this project, will enable industries to reduce the number of iterative steps that are required in product design, production and testing. This will lead to a drastically reduced production time and cost per part. The latter will allow the production of new products and the development of novel applications and systems in several sectors including aerospace, the automotive and the naval industry, medical, optical and precision instruments, as well as computer, audio, video and telecom equipment. The improvements in the reliability, efficiency and speed of production processes will also significantly decrease the scrap rate and reduce the energy needed for production. The corresponding energy savings will help to reduce Europe's CO₂ footprint.

Positive social effects will result from the impact of high-end optical components on the production of new information technology components, mobile electronics and medical devices. Better mechanical alignment through new robotic 3D scanning system tools will be used in advanced particle beam therapies resulting in treatments with higher cure rates. In electrical measurement systems, the project's outcomes will help to better estimate over-voltages and unwanted induced currents in HV lines, as well as in the use of adapted control solutions. This will drastically reduce the loss of electrical energy, which is highly valuable and in high demand in Europe.

The enhancement of advanced manufacturing will help to keep highly skilled jobs in Europe and, hence, it will enhance the employment and wealth of the EU.

List of publications

Maculotti, G., Genta, G., Galetto, M. (2024) 'An uncertainty-based quality evaluation tool for nanoindentation systems', *Measurement*, 225(2) p. 113974. Available at <https://doi.org/10.1016/j.measurement.2023.113974>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 May 2023, 36 months
Coordinator: Sonja Schmelter, PTB Project website address: vidit.ptb.de		Tel: +49 30 3481 7766 E-mail: vidit@ptb.de
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	7. ENS Paris-Saclay, France	15. DUI, Netherlands
2. FFII, Spain	8. IDEKO, Spain	16. FLEXIM, Germany
3. GUM, Poland	9. INTI, Argentina	17. GEOMNIA, France
4. LNE, France	10. PK, Poland	18. KROHNE, Germany
5. VSL, Netherlands	11. POLITO, Italy	19. Mahr, Germany
6. VTT, Finland	12. TEKNIKER, Spain	20. SICK, Germany
	13. UNIPD, Italy	21. TUBITAK, Türkiye
	14. UPM, Spain	



Publishable Summary for 22DIT02 FunSNM Fundamental principles of sensor network metrology

Overview

Sensor networks are used in many fields but are struggling with data quality of varying degrees, unknown measurement uncertainty and lack of traceability to the SI, limiting their applicability. To overcome these issues, this project will address the metrological aspects of generic sensor networks, covering uncertainty propagation, data quality metrics and SI-traceability. In addition, this project will cover the assessment, infrastructure, and risk analysis of distributed sensor networks alongside software frameworks by developing automated applications. The applicability of the methods, tools, and concepts will be demonstrated in typical real-world sensor networks.

Need

Metrology is facing unexplored challenges introduced by the recent developments in sensors, network architecture, in-situ self- and co-calibration techniques, data routing, processing, and Artificial Intelligence (AI) methods, exemplified by Machine Learning (ML) algorithms based on Deep Learning (DL). Their influence on sensor network technologies ranges from areas, such as air quality monitoring and energy networks, to advanced manufacturing. This comes with its own challenges, due to the large volume of data with innate characteristics, such as velocity, volume, value, variety, and veracity.

The quality assurance of sensor networks is important as described in the following Directives: Directive 2010/75/EU of the European Parliament on Industrial Emissions (integrated pollution prevention and control), Directive 2008/50/EC on ambient air quality and cleaner air for Europe, and Directive 2018/2002 – Amendment of Directive 2012/27/EU on energy efficiency. Therefore, novel metrology including traceability, uncertainty assessment, and new calibration techniques for sensor networks is needed to guarantee the quality of their data.

There is a need to develop novel methods or adaptations of the existing methods for uncertainty propagation in sensor networks and for metrological treatment of sensor correlations in data aggregation applications. The development of methods for metrological assessment of distributed sensor networks is also required to establish the trustworthiness of distributed sensor networks over their entire life cycle. In addition, the automated and online implementation of methods developed for large sensor networks, particularly those with characteristics changing on a relatively short timescale, requires the development of new methods and software tools as well as the adaptation of existing approaches to uncertainty evaluation, data quality assessment and traceability.

There is a clear need to develop reliable and accurate methods for the assessment of data quality and measurement uncertainty in real-world sensor networks, such as:

- Advanced manufacturing requires general research to improve the quality of the network-wide measurement data, obtained from existing sensors to control processes and prevent progressive accuracy loss and degradation of product quality.
- City-wide air-quality monitoring networks need in-situ dynamic calibration capabilities to account for their transient nature, as well as methods to facilitate regular recalibration under dynamic conditions.

Report Status:
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METROLOGY PARTNERSHIP



Issued: July 2024

- With an aim of 80–95 % reduction of greenhouse gases from buildings and workplaces, methods for building management must be found through new and smarter digital tools and software frameworks.

Many other areas have similar challenges with uncertainty propagation in sensor networks, and a combined effort to develop tools will provide a suite of generic tools that can be adapted to a wide range of applications.

Objectives

The overall aim of this project is to provide a metrological basis to sensor networks including uncertainty propagation and data quality methods, an assessment of distributed sensor networks, software frameworks and semantics for large transient sensor networks as well as their demonstration in real-world case studies.

The specific objectives of the project are:

1. To develop reliable and accurate methods for the assessment of data quality and measurement uncertainty in real-world sensor networks. The methods will be suitable for a wide variety of sensor networks and should include the propagation of uncertainties, proper treatment of correlations, and uncertainty-aware sensor fusion. Additionally, to produce metrological guidance for data quality metrics in sensor networks that include not only measurement uncertainty but other common factors that can influence data quality.
2. To extend the results obtained in objective 1 to the case of distributed sensor networks, and to develop reliable and accurate methods for their metrological assessments. The methods will cover a wide variety of sensor networks and geographical distributions (e.g., Smart Grid sensors, IoT networks in Smart Cities). Methods will also consider edge and cloud architectures where sensor data is aggregated locally before communication to other parts of the network.
3. To develop reliable methods for the automated application of the methods in objectives 1 and 2, in large transient networks. This requires novel approaches for the handling of information on the individual sensors, their interaction and metrological characterisation, and includes machine interpretable and metrology-aware descriptions for complex sensor networks using semantic technologies (e.g., ontologies). These novel approaches should integrate metrological information on data quality with traceability, as provided by digital certificates and sensor network data protocols.
4. To demonstrate the practical validity of the methods developed in objectives 1, 2 and 3, in at least 3 real-world case studies (e.g., industrial processing, environmental monitoring, building and utility sectors). Using the results of the case studies to develop end user guidance and software for sensor network metrology. The end user guidance will provide improved measurement reliability including (i) standardised methods for in situ metrology, (ii) the use of the software (iii) the use of metrological redundancy, and (iv) error detection.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by end users (industry, advanced manufacturing, environmental monitoring, and energy), standards developing organisations [e.g., Integrated Pollution Prevention and Control (IPPC), Directive 2010/75/EU, Energy Efficiency Directive 2012/27/EU, and Directive 2014/32/EU (MID)], and accreditation bodies.

Progress beyond the state of the art and results

The current state of the art for sensor network metrology is limited to specific applications. For the first time, sensor networks are addressed in a metrologically sound and systemic manner, creating outputs for all areas, where sensor networks are implemented.

Objective 1: In the initial phase of the project, significant progress has been made in understanding and addressing the current state and directions of the sensor network metrology and measurement uncertainties in sensor networks across various applications. This project initially conducted a comprehensive literature review to understand the current state and future directions of sensor network metrology. Addressing the challenges of harmonized metrological approaches, it outlines a future roadmap for the metrological assessment of real-world non-static distributed sensor networks and underlines the importance of joint efforts for a sustainable and reliable future. A comprehensive literature review and stakeholder survey were conducted in some of the most impactful areas including environmental monitoring, energy transmission, industrial manufacturing, natural gas trading, and smart buildings. This information provided valuable insights

into the requirements for uncertainty propagation methods. An assessment of conventional uncertainty propagation methods and existing guidelines was completed, highlighting limitations, and making a foundation for proposing adaptations and new methods to enhance the identified requirements. General uncertainty propagation methods for model-based tree-structured mesh networks were developed and are prepared for publication. These methods will provide artificial measurement points with known uncertainty and investigate the impact of high-quality, traceable nodes on network-level uncertainty reductions. A Laplace domain tool for non-static *in situ* calibration of the sensors and evaluation of their uncertainty analysis was developed, and a scientific paper on these tools is under preparation. Methods for uncertainty evaluation involving correlated sensor data, including temporal and spatial correlations, were also developed, along with a mathematical method for uncertainty calculation with correlated data. A method for estimating the relative drift of sensors in a network was developed for multi-wire thermocouple sensors. This approach includes both data-driven and physics-based models for the sake of drift detection. The project also aimed to identify and assess metrics of data quality to measure the usefulness of sensor network data. A literature review and survey targeting five real-world sensor networks were conducted to identify existing data quality metrics and their shortcomings from a metrological perspective. A survey was conducted to analyse the requirements across the lifecycle of a typical network node, helping to define requirements in various stages, e.g. calibration, deployment, and operation. In addition to the surveys and literature reviews, the project undertook practical evaluations of the proposed metrics and methods within the selected sensor networks. Using the uncertainty propagation methods developed in earlier activities and validation rules, results demonstrated improvements in data reliability and decision-making. Naturally, future work will focus on method refinements and their employment in other sensor networks.

Efforts were also directed towards ensuring SI-traceability in sensor networks through calibration and sensor fusion methods. A survey was conducted to understand the metrological needs related to SI-traceability in various real-world sensor networks, and methods for in-situ self- and co-calibration with reference sensors were investigated. Existing methods for uncertainty-aware sensor fusion in dynamic measurements were identified, and a guideline for extending their applicability to sensor networks is under preparation. A method for uncertainty-aware sensor fusion to detect sensor drift was developed and applied to networks of temperature sensors in heat treatment furnaces and gas flow meters. Potential modelling techniques, such as digital shadow and digital twin, were summarized for smart buildings, district heating and air quality monitoring networks. A comprehensive guidance document on data quality metrics, including measurement uncertainties and assessment of uncertainty-aware sensor fusion techniques, is under preparation and will be available soon. These efforts have laid a strong foundation for the next phases of the project on uncertainty propagation, data quality, and SI-traceability in sensor networks. A summarising open-access paper and a comprehensive guideline will be publicly available soon.

Objective 2: Some of the most used distributed sensor networks were analysed for specific requirements. The consortium has kicked off the work on activities on the characterization and assessment of the distributed sensor networks. This involved surveying the functionalities of such networks and evaluating data metrics and aggregation of the measurement data to ensure accuracy and trustworthiness over the network's lifecycle. Additionally, the work on the evaluation of infrastructure requirements has been started and is focused on identifying and analysing different approaches for creating, extending, and maintaining various types of distributed sensor networks. The project will make substantial progress in the characterisation of fixed and mobile distributed sensor networks considering the data aggregation and trustworthiness across their whole life cycle. The infrastructure aspects, e.g., topology, communication, and access, will be addressed and transformed into architecture design criteria that current methods lack. Risk analysis for the sensor networks will be addressed for the first time in a coherent and standardised manner and its results will be collated in publicly available good practice guides.

Objective 3: To this end, the consortium conducted a comprehensive literature survey on communication protocols and standards relevant to online machine learning methods in sensor networks and calibration applications for hybrid models. This effort developed requirements and scenarios for automating the application of methods founded on the previous tasks, including federated machine learning for distributed sensors. The findings were compiled into a specification report relevant to open-source frameworks MET4FOF and FIWARE. This work was accepted as a review paper for the IMEKO World Congress 2024 and will be presented as part of a talk at the same venue. A cloud-based framework for automatic and online calibration of building performance models was developed, aligned with the IoT Platform FIWARE. The agent framework demonstrated data streaming and analysis in five sensor networks and a guideline document is under preparation on these developments. Additionally, the consortium extended the literature survey with expert

interviews to compile a report on data quality aspects relevant to transient sensor networks. The consortium is exploring modular semantic descriptions of data quality, resulting in a semantic data model and ontology. As a result, this ontology will integrate data quality aspects with metrological traceability which is demonstrated through case studies on smart buildings and industrial heat treatment, ensuring compliance with the FAIR principles.

By the end of the project, automated data handling software frameworks and semantics will be significantly enhanced. This comprises machine-interpretable and metrology-aware descriptions employing semantic technologies. As an outcome, dynamic and distributed measurements in generic large scale transient sensor networks will benefit from the automated methods developed in the project.

Objective 4: Work has started and is progressing well in several key areas over the first nine months. Five use cases have been presented to demonstrate the application of innovative techniques in sensor network metrology. Progress is being made in the employment of uncertainty propagation methods, *in situ* drift detection, sensor fusion and the combination of physical and soft sensors.

The use cases in the project will showcase how the tools developed can be used for improving the state of the art in a suite of representative areas:

- a) Uncertainty propagation in sensor networks will assist in significantly reducing the temperature uncertainty in district heating networks, enabling reduction of the supply temperature, and leading to lower distribution losses.
- b) The improvements in calibration drift analysis will assist in the development of drift determination in multi-wire thermocouples for high-value products, where even small deviations in process temperature can have a significant impact on product quality.
- c) Sensor fusion will aid in the quality verification of gas distribution meters. This will lead to calibrations being performed when needed, rather than at set times, thereby reducing the calibration costs of critical equipment. Metrology for air-quality monitoring networks will be addressed for the first time via automated uncertainty evaluation, data metrics and methods for establishing SI traceability for static and mobile devices. Data aggregation techniques, data fusion methods in the transient heterogeneous environment, and soft sensors will be investigated.
- d) Using optimal combinations of physical and software sensors will reduce installation and maintenance costs while potentially gaining accuracy in smart buildings. This will again lead to improved energy management of the buildings.

Outcomes and impact

Outcomes for industrial and other user communities

In the first phase of the project, the real-world use cases were presented in an IMEKO paper and were accepted for publication. This project has also explored new venues to establish better communication with the industrial sector. For instance, a presentation on "Assessing Parameters Affecting Low-Cost Gas Sensor Response Signals in the European Photoreactor (EUPHORE) Simulation Chamber" was delivered at the Gas Analysis 2024 conference in France and a presentation was delivered to an event titled "W3bsi - Trust Reimagined" in Belgium in May 2024.

In general, outputs from this project are expected to bring significant value to a broad range of industries, ranging from the manufacturing of high-value products to the optimization of district heating and cost reduction in smart buildings. Tools developed for the detection of malfunctioning equipment and derivation of information on the sensor drift *in situ* are relevant for multiple applications and their data quality assessment. This adds value to the manufacturing of high-value products and energy transmission networks.

Good practice guides will directly benefit end users by providing guidance on the metrological assessment of distributed sensor networks with a particular focus on identifying the infrastructure requirements, network architecture, topology, and data aggregation for fixed and mobile sensor networks. The tools developed for uncertainty analysis will enable district heating networks to operate at a much lower supply temperature, significantly reducing heat losses, with immediate impact through financial savings.

The development of data fusion to determine the calibration drift of gas flow meters, individually or in distributed networks, will reduce measurement uncertainty by at least one-third and permit better planning of calibrations.

Novel SI-traceability lowers measurement uncertainties, improves data reliability, and impacts environmental monitoring, with an improved understanding of pollution dispersion, based on static and mobile sensor networks. This informs and empowers decision-makers to monitor and decrease local pollution levels. Improved knowledge of how to optimally combine hardware and software sensors for smart buildings will reduce installation and maintenance costs while improving accuracy.

Outcomes for the metrology and scientific communities

This consortium established a good collaboration with EMN MATHMET and delivered a presentation at the Annual General Meeting of the EMN for Climate and Ocean Observation in France in June 2024. Several EMN representatives also presented their relevant activities in our M9 meeting. In the short time from the start of the project, this consortium submitted four papers: "Gaussian Processes and Sensor Network Calibration," "Automation in Sensor Network Metrology: An Overview of Methods and Their Implementations," "Modelling and Determining Correlations in Sensor Networks," and "Sensor Network Metrology: Current State and Future Directions". The consortium established a stakeholder committee with twenty members and continuously attracts new members. Progress has been made in disseminating knowledge and engaging with stakeholders through our first newsletter, presentations, website, and social media posts. Four key presentations were delivered at international workshops and conferences. These presentations were delivered at the EURAMET TC-T workshop 'Digital Workflows in Thermometry' and the CCT workshop 'Traceability and Dissemination' in May 2024 in France. Another presentation of the project was given at the H2020 VIDIS Final Meeting in Italy.

By the end of the project, the metrological and scientific communities will receive input from working groups, such as BIPM JCGM/WG1, where results from this project can be used as input to a potential supplement to the Guide to the Expression of Uncertainty in Measurements (GUM), and inputs to European Metrology Networks, where several groups are currently dealing with aspects of sensor networks. Additionally, the metrology community will see beneficial outcomes in the tools available for uncertainty analysis of low-cost/low-value sensors in large-volume networks, which are expected to become widespread in the near future. Such sensors are rarely calibrated individually but can bring valuable information when placed in sensor networks.

Outcomes for relevant standards

Participants from this consortium presented their activities in two key engagements. In October 2023, activities were shared with the European standards development organisation (CEN) focusing on air quality sensors (TC 264, WG42) and in April 2024, activities were presented to the national standards development organisation (DS), contributing to S-222 & CEN TC 176.

The project will impact standardisation in several fields due to the generic and widely applicable nature of the research reflected in the use cases. The earliest impact will be on the work programmes of CEN, ISO, IEC, IEEE and WELMEC technical committees and working groups involved in the standardisation related to the industrial, utility, and environmental applications of the use cases studied.

Industry standards such as AMS2750 from Nadcap (National Aerospace and Defence Contractors Accreditation Program) governing heat treatment of high-value components and IEC TC 65/SC 65B/WG5 (Temperature sensors and instruments) can take advantage of the project results. The early impact is expected on the work of ISO/IEC JTC1 SC41 to include metrology and data quality; the documentary standard impacted is expected to be ISO/IEC 30178. The work on the metrological assessment of sensor networks is highly relevant for the IEEE TC10 scope concerned with electronic instrumentation and electrical measurement (several standards e.g., IEEE 1241-2010TM, IEEE 181-2011TM, and IEEE P2414TM).

The standardisation organisations benefiting from the outcomes of the project research and the lessons from the two utility use cases include the WELMEC WG7 'Software' with respect to software and IT components, and WG11 "Gas and Electricity Meters", responsible for a harmonised approach towards legal metrology issues for utility meters. At the CEN level, results are expected to impact the work of CEN TC 176 regarding standardisation in the field of heat meters.

The outputs of this project will be disseminated to CEN-264-WG-42. This committee writes specifications and standards for the validation of air quality sensors, including statistical components. The results of the project are foreseen to impact CEN/TS 17660-1 and the draft technical specification CEN/TS 17660-2 (TC-264-WI-00264179), and possibly future standards on the operation of air quality sensor networks that CEN 264 WG 42 is expected to initiate.

Longer-term economic, social, and environmental impacts

Economic

An estimated 0.54 EJ of energy is lost in European district heating networks each year. A general reduction of the supply temperature from 85 °C to 80 °C will potentially cause a 6 % reduction in heat loss to the ground, resulting in energy savings corresponding to 33 PJ/year, reducing CO₂ emissions by 3 million tonnes per year, and providing financial savings of 2 billion euros.

Extra sensors, required to further reduce supply temperatures without creating health risks, have a potential European market of up to €280 million for hardware components alone, with similar potential revenues for software solutions. In the gas sector, the EU imported 88 billion m³ in the first quarter of 2022, valued at €78 billion. If a current 1 % annual drift in sensor output can be reduced by 30 % through data fusion techniques, a potential €1 billion can be saved per year.

Environmental

Air pollution, linked to 300,000 premature deaths annually in the EU and millions more worldwide, can be monitored more reliably, utilising the tools developed in this project. This will enable decision-makers to focus their efforts. The outcome of this project will support the intention of the EU of becoming CO₂-neutral by 2030, by improving the control and maintenance of utility networks, and by reducing energy consumption in manufacturing, and industrial processing, which accounts for 22 % of European greenhouse gas emissions (joint second highest contributor together with domestic transport; energy supply is the most emitting at 26 %). The improvement in thermometry alone will thus directly improve fuel efficiency and reduce atmospheric emissions.

Social

In the present situation, where fossil fuel prices in Europe have increased significantly, low-income households in Europe (estimated 11 million inhabitants) will have to spend at least 50 % of their current expenditures to compensate for increasing energy prices. Solutions developed in this project will significantly enhance the efficiency of energy distribution networks, resulting in an associated impact on energy savings and prices.

List of publications

No publications yet

Project start date and duration:		1 September 2023, 36 months
Coordinator: Shahin Tabandeh, VTT Tel: +358 50 313 3634 E-mail: shahin.tabandeh@vtt.fi		
Project website address:		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. VTT, Finland	10. AIRPARIF, France	14. RandomRed, Croatia
2. CMI, Czechia	11. FZ-Juelich, Germany	15. Vaisala, Finland
3. DTI, Denmark	12. UH, Finland	
4. FORCE, Denmark	13. VINS, Serbia	
5. IPQ, Portugal		
6. LNE, France		
7. METROSERT, Estonia		
8. PTB, Germany		
9. VSL, Netherlands		
Associated Partners: 16. CCPI, United Kingdom, 17. METAS, Switzerland 18. NPL, United Kingdom 19. UCAM, United Kingdom		

Publishable Summary for 22HLT01 QUMPHY

Uncertainty quantification for machine learning models applied to photoplethysmography signals

Overview

Photoplethysmography (PPG) signals are rich in information and easy to measure passively without any physical or mental limitations of the subject. Machine learning (ML) algorithms are commonly used to extract physiological parameters from PPG signals for diagnosis, avoiding the need for complex and costly clinical review. As of today, no regulations specifying how these ML algorithms have to be applied, how their performance has to be measured or how their associated uncertainties have to be specified exist. At the core of this project stands the development of measures to quantify the uncertainties associated with ML algorithms applied to medical problems, in particular the analysis and processing of PPG signals. To achieve this the following tasks will be addressed: (i) benchmark datasets will be generated using publicly available in vivo, and synthetic data (ii) different ML models and uncertainty quantification (UQ) methods will be used to analyse the processing of the PPG signals and specify the associated uncertainty and (iii) a good practice guide with accompanying software repository showcasing the used models, methods and benchmarks will be developed and made publicly available.

Need

A Photoplethysmograph measures the intensity of reflected or transmitted light through body tissue. Measured at almost any part of the human body (e.g., finger, wrist, arm, ankle, ear, neck), PPG signals change throughout the cardiac cycle as the changing volume of blood present in the tissue influences the intensity of the transmitted/reflected light. PPG signals are used both in a clinical setting and are collected by many wearable devices. They contain valuable information on the cardiovascular, respiratory, and autonomic nervous systems which is not yet routinely exploited. They are popular as they are easy to obtain non-invasively and PPG devices are cheap and widely available. Moreover, using smart devices or even contactless measurements by external cameras yields the possibility for long-term monitoring without restriction of patient comfortability. Until today, an algorithmic evaluation of PPG signals to infer physiological parameters or detect diseases is crucial for saving patients' lives but almost never used in clinical environments. One of the major reasons for this is the lack of trust in the output of any such algorithms.

Due to the vast amount of collected data, machine learning methodologies are essential for the extraction and evaluation of key features used for diagnosis. When applying machine learning in a medical context, however, confidence in the performance and predictions of the algorithms is particularly crucial since diagnostic mistakes can be fatal (false negative) or result in unnecessary anxiety and detrimental overtreatment (false positive). This is supported by the Executive Vice-President for a Europe fit for the Digital Age, Margrethe Vestager, who said "On Artificial Intelligence, trust is a must, not a nice to have". Hence an analysis of the uncertainty associated to ML algorithms and their predictions is indispensable to provide both clinicians and users of wearable devices with critical information about the quality and trustworthiness of the results produced. According to the US Center for Disease Control and Prevention (CDC) over 400 million people worldwide suffer from diabetes with predictions reaching 0.5 billion people worldwide by 2040. Similarly, the World Health Organisation (WHO) estimates that hypertension (elevated blood pressure) affects more than 1.2 billion adults between ages 30 and 79 worldwide with approximately half of the people being unaware that they have this condition or need treatment. A recent EC report states that: "By using digital solutions, such as wearables (...)

Report Status:
PU – Public, fully open

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European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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citizens can actively engage in health promotion and self-management of chronic conditions. This in turn can help control the rising demand for health and care". Wearable devices such as smart watches allow early detection, monitoring and counteracting such conditions through lifestyle and diet changes or early medical treatment potentially saving millions of lives and billions in medical treatment costs. One of the major obstacles of this approach originates from the low signal quality obtained from PPG measurements through smart wearables at e.g., the upper side of the wrist. This again emphasises the need for both ML techniques to process the data, as well as reliable and trustworthy methods to quantify the uncertainties associated to the algorithms' predictions.

The goal of this project is to satisfy these needs by developing an environment, i.e., a good practice guide including a software framework for independent assessment of accuracy and uncertainty of ML algorithms (Objectives 1 and 3) and benchmark cases to test and compare ML algorithms against (Objective 2), to increase trust in ML applications for PPG signals and lay a foundation towards standardisation of ML in healthcare (Objective 4).

Objectives

The overall objective is to provide trustworthy machine learning models for analysing photoplethysmography signals in a medical context, by developing methods for the quantification of uncertainty in supervised machine learning and deep learning models applied to photoplethysmography signals and generating reference datasets to benchmark those models, supported by software being developed that will be publicly available for independent review of the models.

The specific objectives are:

1. To develop methods for quantifying the uncertainty for at least 3 existing classification and 3 existing regression supervised machine learning and/or deep learning models using photoplethysmography (PPG) data, considering the effects of both aleatoric (data) uncertainty and epistemic (model) uncertainty on model predictions.
2. To generate at least 5 measurement problems and their corresponding 5 datasets, using real and/or synthetic photoplethysmography data, that can be used to benchmark accuracy and uncertainty of supervised machine learning and deep learning models. In addition, to make those reference problems and datasets available to the medical device and digital health communities via an online repository.
3. To validate the uncertainties obtained for existing machine learning and deep learning models of Objective 1 and to compare the accuracy and uncertainty of at least 3 classification and 3 regression machine learning and/or deep learning models in order to identify models and methods which have high accuracy and low uncertainty for a wide range of tasks.
4. To engage with the medical device, digital and health communities to (a) promote the use of the good practice guide and the accompanying software repository through conference contributions, peer-reviewed journal articles and stakeholder workshops, (b) support the adoption of the benchmarking problems and datasets by providing guidelines for their use, and (c) develop a framework for independently reviewing machine learning models proposed by industry to assist them in getting regulatory approval.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, medical device calibration services), standards developing organisations (IEC, ISO), and end users (clinical practitioners, digital experts within the health communities, manufacturers of medical and healthcare products).

Progress beyond the state of the art and results

Generate benchmark measurement problem datasets:

Accompanied by leading stakeholders the consortium identified relevant benchmark diagnostic tasks for PPG signals, such as blood pressure determination, detection of atrial fibrillation and classification of hypo- and hypertension. A list of accompanying datasets for the identified benchmark diagnostic tasks has been created and discussed with clinicians and medical device. The datasets have been discussed in view of measurement quality, patient diversity and public accessibility.

The consortium currently evaluates the target communities' feedback to select 5 out of the benchmark diagnostic tasks. With the benchmark problems selected, the consortium will prepare suitable openly accessible datasets and provide them publicly for the projects target user communities. This will be accompanied by publishing a peer-reviewed research article describing the chosen benchmarks and respectively selected datasets and provide examples on how to use them.

Develop methods for quantifying the uncertainty of supervised ML/DL models:

The consortium identified 2 prototypical benchmarks tasks, i.e., blood pressure determination and detection of atrial fibrillation, with accompanying datasets to develop and test machine learning and deep learning models. The models are developed for raw PPG signals, features extracted from the PPG signals and images created from PPG signals. A common evaluation framework to test and compare the performance of the developed methods is simultaneously developed by the consortium to guarantee good scientific practice. The consortium started to investigate several uncertainty quantification methods, such as Monte Carlo Dropout and Deep Ensembles, for their suitability to determine uncertainty for different machine learning algorithms with applications in PPG signals. The uncertainty quantification methods investigated include model dependent and independent approaches encompassing both aleatoric (data) and epistemic (model) uncertainties.

Once the machine learning models and uncertainty quantification methods have been implemented and tested, the consortium will test the performance and uncertainty budget for the selected benchmark diagnostic tasks. The tests will include an investigation of different demographic subgroups of the benchmark datasets, performance of the machine learning models on out-of-distribution data and training performance based on different quality of training data. The results of this evaluation will contribute to a good practice guide on uncertainty quantification for machine learning models applied to PPG signals.

Validation of uncertainties of ML/DL models for the benchmark problems:

The consortium has started to implement a common framework for performance evaluation of machine learning and deep learning algorithms. Additionally, uncertainty quantification methods have started to be developed, including model dependent and model independent methods and methods investigating both aleatoric (data) and epistemic (model) uncertainties. An online repository including the code base for the machine learning and deep learning models, the evaluation metrics and the uncertainty quantification methods has been created by the consortium to track the progress towards the projected outcome of the project. The repository adheres to common software development standards, includes automatic software testing and implements an automatically generated documentation of the repository code. The documentation is updated automatically if the code changes and openly available for public use.

After finishing the development of both machine learning and deep learning methods and uncertainty quantification methods, the joint code base will be used to validate and compare the performance of machine learning and deep learning models for the 5 chosen benchmark diagnostic tasks. The evaluation and comparison will be included in a good practice guide describing the techniques to quantify uncertainties for machine learning models applied to PPG signals. The respective evaluation scripts will be provided within the code repository and will be included as tutorials in the online software documentation.

Engage with medical device, digital and healthcare communities:

The consortium created a stakeholder committee at the start of the project which includes members from the medical device, digital and healthcare communities, which ensures that the benchmark scenarios considered are relevant for and needed by medical device manufacturers as well as clinicians. Additionally, the consortium held a stakeholder workshop to increase visibility of the project and to initiate discussions about future directions of the project. This first stakeholder workshop, conducted in month 3 of the project, provided an overview of the project aims and general structure of the work packages.

The consortium plans to hold a second stakeholder workshop in month 10 of the project. In this workshop the invited stakeholders and other leading experts from clinics and digital healthcare companies will discuss a set of diagnostic tasks involving PPG signals to use as potential benchmark problems. The workshop should result in crucial input for the project and increase the visibility of the project and its future outcomes. At the end of the project, a good practice guide on uncertainty quantification for machine learning models using PPG signals will be created and distributed through the consortium and stakeholder committee to the projects target end user groups. The good practice guide will include a description of the selected benchmark problems and their

respective datasets, a documentation and a user guide for the software repository containing the machine learning and deep learning models, uncertainty quantification methods and the common evaluation framework as well as tutorials showcasing good practice approaches to evaluate uncertainties for the implemented machine learning models and uncertainty quantification methods applied to the benchmarks defined in this project.

Outcomes and impact

In the first nine months of the project the consortium created a stakeholder committee and held two stakeholder workshops. The first stakeholder workshop was intended to foster dissemination of and communication about the project to the project's intended target communities. This was achieved by providing an overview of the project and its planned activities as well as detailed technical discussions about the next steps within the individual work packages. A second stakeholder workshop will focus on input from leading experts, such as clinicians or digital health professionals to ensure a reasonable and practically relevant setup of benchmark diagnostic tasks. Including stakeholders in the selection process improves one of the project's future key outputs and improves dissemination and outreach within the project's targeted end user groups. To improve the outreach of the project even further, the consortium created a website providing detailed information about the project and its projected outcomes. The website also contains a download area providing official project communication documents, a project poster and flyer, the project's corporate design and information about the project's software repository, software documentation and other project related publications.

Outcomes for industrial and other user communities

PPG signals are collected by many wearable devices, such as smart watches, which are now widely available. By making digital health apps based on machine learning available on smart watches, individuals will be able to monitor different aspects of their own health. Combining uncertainty quantification with the machine learning predictions will ensure that only good quality predictions are presented to users which will in turn mean that they learn to trust the predictions and so will continue to use the app. In a hospital setting, pulse oximeters currently monitor patients' heart rate and blood oxygen continuously. By incorporating additional machine learning algorithms into these monitors, many more aspects of a patient's health and well-being could be monitored. Automatic detection systems that give unreliable alarms are often ignored, so the uncertainty quantification will be essential to provide some confidence in the alarms. This will provide continuous monitoring of all patients and will enable early detection of health deterioration.

Outcomes for the metrology and scientific communities

This project will develop new methods for quantifying the uncertainty of machine learning predictions based on PPG signals. The benchmarking datasets will be of benefit to the metrological and scientific communities who may want to use these datasets with their own machine learning models or for other studies. Research papers will be submitted for publication in high impact peer-reviewed journals and the work in the project will be presented at relevant international conferences.

Outcomes for relevant standards

The consortium will contribute to national and international standards and guidelines throughout the project, especially for AI in medicine. Special attention will be given to developing a good practice guide for uncertainty quantification of ML algorithms applied to PPG signals, which can act as a foundation for standardisation of PPG based medical applications in the future. The consortium anticipates high impact of the mathematical tools and advanced uncertainty quantification and propagation methods through international committees.

Longer-term economic, social and environmental impacts

Hypertension, diabetes, and myocardial infarction rank among the most common causes of death in human populations worldwide. Often, especially in the early stages of the diseases, a change in lifestyle and diet can be sufficient to mitigate these diseases, eradicating the need for expensive and possibly harmful treatment or medication. By making digital health apps based on machine learning available on smart watches, individuals will be able to monitor different aspects of their own health. Combining uncertainty quantification with the machine learning predictions will result in more trustworthy predictions. This project will contribute to the rapidly growing digital health industry which is providing wearable devices that enable individuals to continuously monitor their own health and well-being resulting in early detection of health issues or better management of chronic conditions. This will result in better health for users and, in some cases, to a longer life. As a wider

impact, this project will provide a boost to Europe's rapidly growing digital health industry, leading to higher skilled employment and wealth for society, by providing digital healthcare companies as well as clinicians with an understandable and deployable good practice guide to assess the accuracy and uncertainty of ML algorithms in healthcare applications.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 July 2023, 36 months
Coordinator: Nando Hegemann, PTB Tel: +49 30 3481 7773 E-mail: qumphy@ptb.de Project website address: www.qumphy.ptb.de		
Internal Beneficiaries: 1. PTB, Germany 2. CMI, Czechia 3. IMBiH, Bosnia and Herzegovina 4. IPQ, Portugal 5. LNE, France	External Beneficiaries: 6. FC, Belgium 7. FVB, Germany 8. KTU, Lithuania 9. THM, Germany 10. UGent, Belgium 11. Uni-Oldenburg, Germany	Unfunded Beneficiaries: -
Associated Partners: 12. KCL, United Kingdom 13. NPL, United Kingdom 14. SectorHealth, United Kingdom 15. SURREY, United Kingdom 16. UCAM, United Kingdom		



Publishable Summary for 22HLT02 A4IM Affordable low-field MRI reference system

Overview

Low-field magnetic resonance imaging (MRI) is experiencing a renaissance: these systems are cheaper, safer, more adaptable to different environments, and easier to use than their high-field counterparts. Compact and mobile scanners are changing workflows in radiology, where MRI comes to the patient rather than the patient to the MRI. These innovations are driven primarily by Artificial Intelligence (AI) combined with low-cost hardware customised to clinical applications. This project will establish the necessary metrological framework for the harmonised development of clinical low-field MRI to facilitate greater access to this technology and ensure reliable and reproducible diagnostic information for patients in the EU and worldwide.

Need

Around 40 million MRI scans are performed in the EU each year. The number of examinations is unevenly distributed among the member states, to such an extent that the number of MR scans per million inhabitants is 26 times smaller in Cyprus compared to Germany, while in many non-EU countries MRI is not available at all.

Low-field MRI offers the potential for greater access to this critical diagnostic technology through more portable scanners opening the possibility of scans in the patients home or in intensive care units. Despite low-field scanners being more affordable than their high-field counterparts, proprietary low-field MRI units are still relatively costly to purchase, operate and maintain. This prevents most hospitals, doctors' offices, research institutions, metrology institutes and companies from purchasing or using these scanners to advance healthcare, science, and technology. Low-field MR scanners based on open-source hardware designs operated by open-source software will change this paradigm. First prototypes demonstrated a truly affordable (< 50 k€ material cost) alternative with image quality comparable to commercially available scanners. A strategy that is fully in-line with the recent resolution of the UN Economic and Social Council asking to "better leverage open-source technologies for sustainable development" and latest EU4Health Programme 2021-2027 which focuses on "supporting actions to enhance the availability, accessibility and affordability of medicinal products [...]". By increasing MRI affordability based on greater low field MRI uptake, medical practitioners and their patients will have more portable reliable and robust tools to assess a wide range of different neurological and orthopaedic conditions based on the quantitative T2 and T1, rho methods developed. Mapping of these factors enables primary brain cancer tumour types to be distinguished and supports Europe's Beating Cancer Plan established in 2021 where "early detection" and "diagnosis" are one of its four key pillars. These quantitative parameters are also used to successfully identify patients at risk from osteoarthritis which affects more than 40 million people in the EU and is the "fastest growing cause of disability worldwide". These quantitative parameters also have potential for use in the detection of the onset of ischemia - a key factor for stroke patient treatment.

To scale these low-field MRI innovations and increase use, a metrological framework to support and boost the development and application of affordable open-source low-field MR systems is needed. This must include metrologically characterised reference systems for benchmarking (objective 1 and 3) and software for scanner control, image reconstruction and data processing (objective 2). Modular strategies to medical device development need to be established including open-source documentation blueprints of hardware and

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: July 2024

software according to the requirements of the EU's medical device regulation (EU)2017/745 (MDR) (objectives 1 and 4). This will improve access to this essential technology, facilitate adoption by clinical end-users and unleash the vast innovation potential of this technology.

The consortium benefits from a strong participation of companies who can directly utilise the outcomes of this project. Project stakeholders include low-field MR vendors, electronics and RF hardware companies, software companies specialised in cloud-based solutions for MR data acquisition and deep-learning based image reconstructions.

Objectives

The overall goal of this project is to establish affordable open-source low-field MRI systems covering hardware components, data acquisition and image reconstruction within the EURAMET network, which are reproducible, fully documented and metrologically characterised. The specific objectives of the project are:

1. To design, develop and evaluate mobile (< 300 kg), low-cost (< 50 k€) and fully replicable low-field MRI reference systems (main static field $B_0 \approx 50$ mT), capable of imaging the human head and extremities. This includes the full characterisation of these reference systems by metrologically validated methods including B_0 , radiofrequency and switched gradient fields. To furthermore draft the technical documentation for the design and production process of the reference systems in accordance with the requirements of the EU medical device regulation (EU)2017/745 and to distribute the complete documentation of the system under open-source licences.
2. To develop accurate and fast image reconstruction techniques for the low-field MRI reference systems from Objective 1, and to enable quantitative imaging of biophysical parameters using these systems based on combining hardware models and MR signal models with physics-informed deep learning approaches. Access to these reconstruction techniques is to be enabled by the implementation of an open cloud-based platform to facilitate reproducibility studies and the benchmarking of commercial low-field systems against the developed low-field MRI reference systems.
3. To evaluate the clinical suitability of the developed low-field MRI reference systems by standardised testing to assess imaging performance across sites involving clinical radiologists. In addition, (i) to perform multisite reproducibility studies and to evaluate the uncertainties of the constructed low-field MR scanners under different operational conditions (e.g., thermal fluctuations or electromagnetic interferences) and (ii) to compare the performance of these reference systems and their uncertainties to commercially available low-field MR systems ($B_0 = 0.05 - 0.6$ T) in inter-vendor comparisons.
4. To facilitate the adoption of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g. accredited laboratories, instrumentation manufacturers), standards developing organisations (e.g. IEC TC 62/SC 62B), and end users (e.g. clinical community).

Progress beyond the state of the art and results

Objective 1: Mobile, low-cost and fully replicable low-field MRI reference systems

Current low-field MR systems ($B_0 \sim 50$ mT) can be brought directly to patients, but they use iron yoke magnets leading to a weight > 600 kg.

In this project a Halbach magnet design was adopted making the scanner 3-4 times lighter and smaller. The components were designed such that the construction does not require specialised machines and is safer, facilitating local production and repair. The CAD designs and information about simulations of the different components are all made publicly available under an open-source licence. Additional open-source tools to carry out quality control of e.g. individual magnets have been developed.

Investigations of improved RF shielding or novel contactless sensors for patient monitoring will allow for safe, stable and high quality low-field imaging under varying environmental conditions. The system will be fully characterised and all information to rebuild, operate and maintain these scanners will be shared publicly and freely under open-source licences for other metrology institutes, research groups, companies etc. to be reproduced. The estimated total cost over 10 years will be $1/10^{\text{th}}$ of the current cost of low-field systems. Providing open-source documentation fulfilling the requirements of the EU medical device regulation (EU)2017/745 facilitates the approval for similar low-field MR systems by companies and an easier

assessment by notified bodies, which culminates in cost savings for public healthcare systems. The fully characterised reference systems will provide excellent and necessary testbeds to investigate safety related aspects of low-field MRI on vendor-neutral transparent systems to improve current standards (IEC 60601-2-33).

Objective 2: Open-source platform with model-based image reconstruction techniques

Image reconstruction for low-field applications is still in its infancy. There are image reconstruction and correction algorithms developed specifically for low-field applications, but these are proprietary products relying on proprietary AI solutions, making it extremely challenging to reproduce results, to innovate and to benchmark inter-vendor performance. This project will provide an open-source platform with model-based image reconstruction approaches optimised for the challenges of low-field low-cost MRI (e.g. low SNR due to the small magnetic field and hardware limitations due to cost-effective design).

A deep-learning based approach for quantitative MR reconstruction was developed which combines knowledge about the MR signal generation and data acquisition with a learned regularisation. An unrolled alternating optimisation was used to obtain the best possible quantitative maps of (bio-)physical parameters which adhere to the underlying physical models and are consistent with the acquired MR raw data. This required the development of differentiable optimisation blocks which can be easily extended to a wide range of different quantitative MR applications. Numerical simulations and in-vivo studies demonstrated that our proposed end-to-end approach yields more accurate parameter maps with higher image quality compared to previously presented methods which often only take the MR data acquisition or the MR signal model into account.

A database with MR raw data acquired from low-field scanners will be created and made publicly available to enable comparisons and foster further developments. Cloud-based solutions to operate and maintain the MR scanners will ensure the utilisation of complex image reconstructions without the need for high-end local computing power.

Objective 3: Evaluation of the clinical suitability and comparison to other low-field systems

For the first time multiple low-field low-cost open-source MR scanners will be built at different sites and evaluated. This will establish a long-lasting framework for metrology in this growing field. The performance of the constructed reference scanner will also be compared to commercially available low-field MR systems of similar ($B_0 = 50$ mT) and higher ($B_0 = 0.2 - 0.6$ T) field strengths.

Five low-field MR systems have been selected for comparison with the developed reference system and additional in-vivo studies. Ethical approval for the in-vivo studies has been obtained.

This will give important results to evaluate signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR) and image quality for clinical use over a variety of low-field strengths. The open-source nature of the project allows the developed hardware, software, pulse sequences and image reconstruction techniques to be easily translated to other low-field MR systems improving their imaging performance.

Outcomes and Impact

Key dissemination and communication activities

Two scientific articles were published and ten presentations at international conferences were given.

The concept of our portable open-source low-field MR scanner combined with AI-based image reconstruction at the HANNOVER MESSE 2024, one of the most important platforms for current innovations and new exciting products with more than 100000 visitors. For this event also a video on open-source portable low-field MRI was created.

A workshop together with stakeholders was organised to finalise a human-centred design of our low-field MR scanner and ensure that this device can easily be moved around a hospital and allow straight-forward scanning of patients.

We carried out six hackathons including also people from outside the project to develop scanner control and image reconstruction software collaboratively.

Eight news posts on our project website and five LinkedIn posts were created.

Outcomes for industrial and other user communities

The innovative low-cost reference low-field MRI (e.g. novel magnet design, embedded sensor technology, novel pulse sequences and image reconstruction techniques) can be easily benchmarked and translated into novel products by MR vendors decreasing time-to-market drastically. Its open-source user interface and imaging platform is based on transparent interfaces to MR console hardware (Pulseseq) and MR image reconstruction (ISMRMRd) making it easily adaptable by MR manufacturers to their products, while the large scientific community can feed into the development of the image processing pipeline. The project's cloud-based user interface and reconstruction platform will create an accessible and secure EU infrastructure for research institutions and other healthcare stakeholders globally and thus supporting the World Health Organisation's 4A (available, accessible, appropriate, affordable) strategy for medical devices. These developments address the current gap in healthcare access to diagnostic MRI for patients across the EU member states in accordance with the EURAMET 2030 Strategy to "Develop and maintain an appropriate, integrated and cost-effective measurement infrastructure for Europe aligned to the needs of society and industry".

Outcomes for the metrology and scientific communities

Current low-field systems are highly integrated commercial devices using deep-learning based image reconstruction algorithms tightly bound to proprietary hardware modules. These are commonly too expensive to purchase and operate for most NMIs. The affordable low-field MR scanners developed in this project will enable more European NMIs to operate and offer services for MRI scanning and will establish a metrological network enabling further collaboration and development. This will strengthen the competitiveness of European NMIs and broaden their portfolio of services in the emerging field of low-field MRI. The developed reference low field MR system will provide a workhorse for innovations, ensure best possible comparability between different systems, foster the translation of novel hardware and imaging techniques into clinical products and facilitate the evaluation of AI algorithms. The project's MRI system will help promote qualitative and quantitative MRI by addressing the need to evaluate the robustness and explicability of deep-learning based approaches, as well as assessing portable low-field MRI uncertainties under varying conditions. The project developed MR hardware will enable benchmarking against commercially available MR systems improving the scientific and clinical evaluation of MR techniques and spurring innovation through improved reproducibility.

Outcomes for relevant standards

Open-source hardware can be reproduced for 1/10th of the price of commercially available products and the availability of a modular technical documentation according to MDR (EU)2017/745 will allow for a much easier transition towards certified products. This project, by offering open-source and modular hardware documentation and technical documentation for the low-field MR reference system to MDR (EU)2017/745 requirements will facilitate increased reproducibility of MR systems and improve their safe operation. This novel approach will provide a blueprint for meeting MDR (EU)2017/745 requirements as an aid to future developments of open-source MR scanners by industry and academia. It will also be adaptable to other medical imaging modalities, e.g. by the echoOpen Foundation developing open-source ultrasound systems. Fully characterised and transparent imaging systems are important for the implementation of the EU Artificial Intelligence Act. The EU trustworthy AI paradigm requires AI to be technically robust and reliable in its outcomes. This project will generate important results to support industry in demonstrating, and regulatory bodies in evaluating the safety of novel and implemented AI algorithms.

Even though low-field MR scanners might be considered to be safer than higher field ($B_0 > 1.0$ T) systems in many aspects such as stray magnetic field, acoustic noise, peripheral nerve stimulation or SAR, the most important MR safety standard, the IEC 60601-2-33:2022 "Particular requirements for the basic safety and essential performance of magnetic resonance equipment for medical diagnosis", currently does not take this into consideration, making regulatory approval unnecessarily complicated. The project results will provide a major contribution to future editions of the IEC standard (e.g. edition 4.1 of IEC 60601-2-33), simplifying current procedures for safety evaluation of low-field MRI. This will improve the innovation potential of this technology, reducing costs and improving global accessibility. The developed reference hardware will furthermore enable investigations into the safety of low-field MR systems ($B_0 < 0.1$ T) for patients with passive and active implants, providing important results to ASTM F2182 and ISO/TS 10974.

Longer-term economic, social and environmental impacts

The economic and social impact of this project is well aligned with the goals of the United Nations Economic and Social Council, who passed E/RES/2021/30, and invited to find "...ways to better leverage open-source technologies for sustainable development...". The market value of medical imaging was estimated as more than 28 billion USD in 2021 and expectations for 5 % growth over the next 10 years. MRI is growing even faster at a rate of 6.5 %. This project will create a MDR (EU)2017/745 blueprint for new innovations in low field MRI systems helping to keep Europe at the forefront of the medical imaging market.

This project's affordable low-field MR system has potential to initiate other systems that will be a game changer for radiology. MRI will no longer be an expensive imaging modality, mostly restricted to hospitals and used only for a limited number of conditions, but it will be able to move into the local doctors' surgery and even to the patient's bedside, with similar portability to that of ultrasound scanners. This will open new possibilities in healthcare such as: monitoring critically ill patients in intensive care units without needing to transport them through the hospital, monitoring stroke and expanding acute stroke care, screening patients with mild traumatic brain injury using less high-field MRI and/or reduced radiation exposure with Computed Tomography. This will transform MRI from a specialists' tool to an easy-to-use first choice for many clinical applications worldwide.

The project's open-source modular MR scanner is built from low-cost materials and uses readily available production facilities, with all necessary documentation provided so that repairs can be easily carried out by users without special training at low cost. This will increase the systems lifetime and offers CO₂ manufacturing reductions as fewer replacement scanners will be needed, addressing the expectations of the European Sustainable Products Initiative which will build on the Ecodesign Directive 2009/125/EC. By providing all the necessary documentation and ensuring a hardware design that can be easily replicated, the project's open-source low-field MR system is fully aligned with these developments within the European Green Deal programme.

List of publications

Zimmermann, Felix F. et al (2,024) 'PINQI: An End-to-End Physics-Informed Approach to Learned Quantitative MRI Reconstruction', IEEE Transactions on Computational Imaging, 10(1) p. 628-639. Available at <https://doi.org/10.1109/TCI.2024.3388869>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	6. CSIC, Spain	16. BRAIN-LINK, Germany
2. CMI, Czechia	7. CTU, Czechia	
3. INRIM, Italy	8. FHDO, Germany	
4. LNE, France	9. IUC, Türkiye	
5. TUBITAK, Türkiye	10. KAR, Czechia	
	11. LUMC, Netherlands	
	12. OREG, Germany	
	13. OVGU, Germany	
	14. STU BA, Slovakia	
	15. UMCF, Germany	
Associated Partners: 17. ETHZ, Switzerland, 18. KCL, United Kingdom, 19. UNIABDN, United Kingdom		

Publishable Summary for 22HLT03 AlphaMet Metrology for emerging targeted alpha therapies

Overview

Targeted alpha therapy (TAT) is a rapidly growing cancer treatment modality, whereby alpha-emitting radiopharmaceuticals selectively target tumours whilst minimising the radiation to healthy tissues. Presently only $^{223}\text{RaCl}_2$ has regulatory approval, but its success resulted in unprecedented levels of interest and investment in TAT for a variety of cancers. It is showing promising efficacy and increased survival in clinical trials; however, several unmet and unique measurement challenges remain a barrier to enable the safe and optimised implementation of emerging targeted alpha therapies. This project will provide the metrology needed to support end-to-end traceability before wide routine adoption.

Need

Global cancer incidence is projected to increase 47 % by 2040 with 28.4 million new cases each year. Europe's Beating Cancer Plan recognises the need for personalised cancer treatments and encourages the development of novel radiation therapies like TAT. The success of $^{223}\text{RaCl}_2$, the first and only with marketing authorisation for advanced prostate cancer, resulted in unprecedented levels of interest and investment in this promising treatment modality with new treatments based on ^{227}Th , ^{225}Ac , ^{212}Pb , or ^{211}At undergoing clinical trials.

The short range and high energy of alpha particles is showing promising treatment efficacies even in patients not responding to its beta-emitting analogue therapy. However, these advantages bring new measurement challenges including the lack of validated primary (secondary) activity standards, the in-growth of the decay progeny, the separation of the decay products, or the quantification of the microscopic distribution of activities and absorbed dose *in-vivo*. The best approach to deliver TAT is under debate and good practice guides are not available, with treatments currently administered with fixed radiopharmaceutical activity levels and not guided by dosimetry. This is in contrast to external beam radiotherapy, where treatments are traceable to primary standards and accuracy in dose delivery to patients is below 5%. The accuracy, reproducibility, and uncertainties in the delivery of TAT are presently unknown, with a recent ICRU Report 96 highlighting the need to address the lack of traceability and standardisation/harmonisation.

An estimated 6 million annual therapies are already delivered across more than 1,500 nuclear medicine centres in the EU, and unprecedented levels of demand for TAT are expected in coming years (100-fold). It is therefore of vital importance to facilitate accurate measurements with minimal uncertainties to improve confidence and evidence in the safe routine implementation of personalised TAT, required to support 2013/59/EURATOM and other regulations.

Objectives

The overall objective of the project is to address the unique and unmet metrological challenges of targeted alpha therapies. The specific objectives of the project are:

1. To develop and validate **primary and secondary radioactivity standards** with traceability to national standards and low uncertainties that consider decay chain progeny in-growth and the separation of

Report Status:
PU – Public, fully open

Publishable Summary

Issued: July 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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decay products for alpha-emitting radionuclides such as ^{211}At , $^{212}\text{Pb}/^{212}\text{Bi}$, ^{224}Ra , ^{225}Ac , and ^{227}Th . In addition, clinical therapy requirements and achievable clinical measurement accuracies will be assessed by an inter-comparison exercise

2. To provide guidance for clinical stakeholders on organ **activity quantification methods** using external monitoring systems and nuclear medicine imaging. This is to be achieved by: (i) the development of methods to quantify the separation of the decay products during imaging at the required levels of therapy activity; and (ii) the performance of a comparison exercise to assess the accuracy, reproducibility, and the quantification of uncertainties of the developed methods in a clinical setting.
3. To establish **accurate alpha-emitter dosimetry calculations** that enable compliance with 2013/59/Euratom and the assessment of the true dose response relationships. This is to be achieved by: (i) the validation of dosimetry pharmacokinetics models for TAT; (ii) the determination of the uncertainties from measured activity to absorbed dose, including the identification of major factors affecting accuracy and precision for alpha emitting therapies; and (iii) the determination at the tissue level of the significance of mean dosimetry for highly heterogeneous distributions of alpha emitters.
4. To determine a **multi-modality imaging protocol that considers differences in bone density and marrow cellularity between individual patients based on: (i) a test object** manufactured by 3D printing technology that incorporates relevant tissue-equivalent materials and geometric complexity for the assessment of treatment toxicity and (ii) bone marrow dosimetry.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain and end-users (e.g., pharmaceutical as well as medical and healthcare products manufacturers, clinical QA laboratories and clinical stakeholders) and the relevant organisations in the context of the regulation (e. g. EANM, EFOMP, IAEA, EURADOS).

Progress beyond the state of the art and results

Realisation, validation, and dissemination of radioactivity standards – objective 1

Revision of secondary standards for ^{223}Ra in 2015 showed a 9% discrepancy with previous data and highlighted the importance of traceability to primary standards and international comparison exercises. Primary and secondary standards will be developed for emerging alpha emitters ^{225}Ac , ^{212}Pb and ^{211}At to enable traceable activity measurements for TAT in (pre)clinical centres, hospitals, and production sites. The robustness of activity standards will be assessed through inter-laboratory comparison and submission to the BIPM-SIR. To meet the needs of end-users, the time-dependence of calibration factors will be investigated when parent-progeny equilibrium conditions are not reached. The metrological traceability and accuracy of radionuclide activities administered to patients and used by (pre)clinical research centres, will be improved via a multi-centre intercomparison using radionuclide calibrators and gamma counters. The intercomparison will be preceded with a comprehensive survey among clinical and preclinical centres which will be launched in autumn 2024. The survey will map the needs of the end-users and based on the output metrological gaps in the traceability chain can be identified and filled by new services.

In-vivo activity quantification with SPECT in TAT – objective 2

Quantitative SPECT imaging is not established for alpha emitters, with a range of protocols used for acquisition and post-processing analysis. This project will use in-silico models of clinical SPECT scanners validated via experimental phantom measurements to optimise 3D imaging acquisition parameters and activity quantification methods, with traceability to the newly developed standards. The generated ground-truth data will be used to optimise methods to quantify long-lived decay progeny that may redistribute to other tissues, image reconstruction and correction methods to improve image quality and accuracy of activity quantification with known uncertainties. A standard protocol will be developed and used to perform the first multi-centre comparison of SPECT nuclear imaging for alpha emitters, providing knowledge on the levels of accuracy, reproducibility, and uncertainties achievable for harmonisation. This will provide recommendations for the harmonisation of quantitative imaging following TAT and will identify the major factors that impact accuracy and need further improvements. Major manufactures of SPECT scanners are members of stakeholder committee which allows for faster implementation of project research outputs and recommendations into clinical praxis.

Quantification of absorbed doses in TAT – objective 3

The ability to quantify the distribution of alpha emitters *in-vivo*, enables the possibility to incorporate dosimetry to optimise the treatment instead of using a 'one size fits all' approach with fixed administered activities. Accurate dosimetry relies on accurate knowledge of the spatial and temporal activity distribution and dose conversion factors. Commonly used clinical (macro)dosimetry methods assume a uniform uptake and no redistribution of daughters from the parent radionuclide. A framework will be established in this project to assess the impact and errors associated with these assumptions through autoradiography, pharmacokinetic modelling and microdosimetry for TAT, including methods to assess the uncertainties in the activity to absorbed dose measurement chain. Within the project developers and users of 3 different autoradiography systems (Alpha Camera, iQID, Beaver) for alpha emitters have been brought together in order to test, improve and calibrate their systems in a unified way.

Towards personalised bone marrow dosimetry through quantitative morphological imaging – objective 4

The red marrow is considered a dose-limiting organ at risk that can limit the administered activity, making marrow dosimetry essential for safety. Reference models for marrow dosimetry are based on relatively simple skeletal models. Variations in bone density, and red and yellow marrow contents can introduce errors of up to 200 % on red marrow dosimetry for alpha emitters depending on bone site and age, making it highly patient-specific. This project will evaluate the potential to incorporate patient-specific bone marrow morphology measures into dosimetry calculations through the development of bespoke phantom and morphological imaging protocols based on MR and dual-energy CT imaging.

Outcomes and impact

This project, in collaboration with the BIPM CCRI RTQI Working Group, launched a first stakeholder workshop in February 2024. The International Workshop on Standards and Measurements for Alpha Emitting Nuclides in Therapeutic Nuclear Medicine was hosted by BIPM and brought together global experts from the fields of radionuclide metrology, industry (such as pharmaceutical, radionuclide producers, scanner manufacturers), clinical nuclear medicine, medical physics, and radiochemistry, 60 attending in person and 235 online. This two-day event was very well received by the audience and based on its success, two more workshops are planned for 2025 and 2026. In addition, this project presented their results to EURAMET TC-IR (Ionising Radiation) and to International Committee for Radionuclide Metrology Gamma spectrometry working group and Life sciences working group. The project also gave 12 presentations to national and international events and collaborated with other projects, such as EPM JRP 20NRM05 iMET, PRISMAP Horizon Europe project and SECURE ENEN project.

Outcomes for industrial and other user communities

This project is the first international effort to provide metrology support for the determination of end-to-end measurement uncertainties and for improving methods to quantify activity and absorbed doses for alpha-emitting radiopharmaceuticals. The provision of validated radioactivity standards for currently unavailable alpha-emitting radiopharmaceuticals will enable the dissemination of traceability from NMI/DIs and will provide access to improved capabilities for national and accredited laboratories in Europe, supporting consistency in activity measurement capabilities. New standards with recommendations for improving measurements will benefit the end-users that rely on such calibration services, including manufacturers of ionising radiation measurement instruments (radionuclide calibrators, gamma counters, imaging scanners), radionuclide production facilities, and pharmaceutical companies. Currently 4 pharmaceutical companies and two nuclear medicine imaging scanner manufacturers are members of the stakeholder committee and more than 10 European hospitals are collaborators to the project.

Hospitals delivering TAT will be able to administer treatments with traceable activities, with accuracies within the limits recommended by the IAEA. The recommendations for good practice will be of benefit to end-users like healthcare professionals in hospitals and the pharmaceutical industry, providing them with methods to standardise and harmonise imaging and dosimetry methods with robust uncertainty budgets. This will improve reproducibility in multi-centre studies and enable comparison of results, providing greater statistical power to study correlations between absorbed dose and response/outcome measures which are still lacking for TAT. This will provide the basis for evidence-based treatments, facilitating regulatory compliance and marketing authorisation of upcoming alpha radiopharmaceuticals for the pharmaceutical industry, and potentially reducing the development costs by introducing metrology early before routine implementation of TAT.

Outcomes for the metrology and scientific communities

Standardisations and improved decay data for alpha emitters will be validated through inter-laboratory comparisons organised by the participating NMIs and linked to the BIPM International Reference System (SIR) to provide a route to demonstrate their accuracy, consistency, and independence, which in turn will support regulatory compliance. Some of the participating members are new to a EURAMET project, which will promote knowledge transfer between the scientific community and metrologists, building networks that will lead to opportunities for further research. Knowledge of activity standardisation techniques will be shared amongst NMIs.

A recent report by the European Commission identified the need for investment towards a sustainable and resilient supply of medical radionuclides in the EU as key to meeting future demands, in particular for alpha emitters. These challenges are presently being addressed by other ongoing initiatives such as Horizon 2020 PRISMAP or the NOAR COST Action project. The outcomes of this project will complement and expand on these initiatives by addressing the measurement challenges of establishing traceable and harmonised measurements to guide the use of upcoming TAT in a clinical setting.

These and other initiatives will create and strengthen opportunities and collaborations between metrologists and the scientific community, increasing the competitiveness and international recognition of the European metrology infrastructure. The project outputs will be disseminated to the scientific research community and other stakeholders via reports and recommendations, peer-reviewed publications in high-impact scientific journals, presentations at national and international conferences, and through engagement with the IAEA and international societies such as the EANM, EFOMP and EURADOS.

Outcomes for relevant standards

The improved end-to-end measurement traceability provided in this project, from the provision and dissemination of activity primary and secondary standards to the provision of recommendations for accurate imaging and dosimetry with known uncertainties for alpha emitters, will support EU directive 2013/59/EURATOM mandating dosimetry-guided radiopharmaceutical therapies (including TAT), but also 2001/83/EC for medicinal products, and 2001/20/EC for clinical trials.

The experienced consortium will promote the results of the project within the standardisation community and through involvement with international technical committees, including organisations establishing international equivalence for radioactivity measurements (BIPM, EURAMET TC-IR) through the development of radionuclide metrology techniques (ICRM). Good practice guides and recommendations to standardise and harmonise imaging and dosimetry for TAT will be disseminated and promoted within the International Atomic Energy Agency (IAEA), European Association of Nuclear Medicine (EANM), the European Federation of Organisations for Medical Physics (EFOMP), and the European Radiation Dosimetry Group (EURADOS). In particular, the results of a multi-centre comparison exercise of clinical quantitative SPECT imaging for alpha emitters will be of interest to the EANM Forschung GmbH (EARL) initiative establishing accreditation programmes for the harmonisation of nuclear medicine imaging. However, it should be noted that some of these processes can be lengthy and extend beyond the duration of this project.

Longer-term economic, social, and environmental impacts

One in 2 people will develop cancer in their lifetimes and as life expectancy increases, the number of patients needing cancer treatment rises. According to an international project by the Lancet Oncology Commission, a comprehensive scale-up of imaging, treatment, and care quality would avert 9.55 million (12.5%) of all cancer deaths, saving 232.30 million life-years. Scale-up of imaging would cost US\$6.84 billion in 2020-30 but yield lifetime productivity gains of \$1.23 trillion worldwide. Therefore, any advancements towards improving image quantification for emerging novel cancer treatments like TAT will have a major positive economic impact.

The development and translation of new TAT for a variety of cancers is rapidly growing with a global market size of US\$ 672 million that is expected to grow 36.7% by 2027. As an example, due to the high incidence of prostate cancer, which is a prime candidate for TAT, an unprecedented level of demand is expected, with 350,000 patients being potentially eligible for ^{225}Ac -PSMA therapy in coming years if following the same trend as its beta-emitter analogue ^{177}Lu -PMSA. In the UK, the number of $^{223}\text{RaCl}_2$ treatments increased by 100-fold in three years following its approval, further highlighting the potential rate of demand. The traceability for TAT provided by this project is therefore of major importance to support the logistical and scientific challenges that European nuclear medicine departments will face in the imminent future.

The implementation of metrology to support the development and use of alpha-emitting radiopharmaceuticals has a fundamental role in the provision of cost-effective cancer treatments that improve patient outcomes with minimal toxicity. Improved knowledge of the decay data, traceable measurements of activity as well as harmonised imaging and dosimetry protocols for multi-centre studies will provide robust tools and confidence to enable personalised dosimetry-based treatment planning and treatment verification as required by the Basic Safety Standards Directive. The outcomes will also indirectly contribute towards increasing confidence in radiation protection measurements for handling of radioactive material during the delivery of TAT.

On a wider impact scale, the developed innovative approaches and new collaborations established between measurement laboratories and stakeholders will be open to further exploitation and lead to new services and products relating to activity measurements, imaging and dosimetry calculations for TAT that can result in higher employment rates and wealth for society across Europe and worldwide.

List of publications

No publications yet.

Project start date and duration:		1 st September 2023, 36 months
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Project website address: https://alphametproject.com/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CMI, Czech Republic	7. BfS, Germany	13. ARRONAX, France
2. CEA, France	8. KU Leuven, Belgium	
3. CIEMAT, Spain	9. KUM, Germany	
4. ENEA, Italy	10. OSA, Spain	
5. NCBJ, Poland	11. UGOT, Sweden	
6. SCK-CEN, Belgium	12. UKW, Germany	
Associated Partners:		
14. CHUV, Switzerland,		
15. NPL, United Kingdom,		
16. RSFT, United Kingdom		
Affiliated Entities: 17. BB, Spain (linked to OSA)		

Publishable Summary for 22HLT04 MetrINO Metrology for innovative nanotherapeutics

Overview

Europe is facing significant healthcare challenges driven by an ageing population coupled with an increase in chronic diseases like cancer, diabetes, heart disease, and brain conditions. These conditions require diverse and complex treatments, which increase healthcare costs. Nanomedicine and nano-enabled medical devices therapeutics (defined here as nanotherapeutics) are vital for tackling health and societal challenges, providing versatile technical solutions. This project responds to the immediate metrological needs expressed by industry, regulatory agencies, and policymakers to develop and validate traceable measurement methods and reference materials (RMs) candidates for the assessment of the critical quality attributes of nanotherapeutics. The project focuses on clinical formulations, including synthetic lipid-based nanotherapeutics, lipid nanoparticles (LNPs) for RNA delivery and liposomes, and metal oxide nanoparticles (MONPs) used for localised cancer treatment, gene therapy, vaccines (e.g. COVID-19) or as contrast agents. By providing fit for purpose methodologies, standardised methods and RM candidates to regulators and industrial stakeholders, the project is supporting their clinical translation, providing more efficacious nanotherapeutics with fewer side effects to improve the patient's quality of life and enhancing the competitiveness of the European health technology industry.

Need

Nanotechnologies offer improved treatment of diseases through the effective targeting of therapeutic agents. Approved clinical formulations include (i) liposomes for cancer treatment, (ii) lipid-based nanoparticles for vaccination (COVID-19) and gene therapy, and (iii) metal oxide nanoparticles for local tumour treatment or as contrast agents. In their strategic paper, 'Regulatory Science to 2025', the European Medical Agency (EMA) states that, with the approval of innovative nanotherapeutics, it is crucial to 'develop and standardise new testing methods related to the quality and safety assessment of nanomedicines', to reach an understanding of 'the critical quality attributes of a given product and the relationship between those and its biological activity and in-vivo behaviour'. Recently, the European Commission's Joint Research Centre (JRC) identified general priorities for method development and standardisation of nanotherapeutics, including methods to measure: (i) surface properties, (ii) stability and kinetic properties in biological media, and (iii) uptake, absorption, and distribution in cells and tissues.

Industrial stakeholders have expressed similar measurement needs, specifically associated to different classes of nanotherapeutics. For example, stakeholders identified that MONP reference materials and fit-for purpose methodologies for their synthesis and characterisation are lacking. Improved methodological approaches are needed to measure (i) the particle size and morphology of small and not spherical particles, (ii) the amount, homogeneity, and functionalisation of the nanoparticle surface and (iii) for the detection of nanoparticles *in vivo*.

For liposomes and LNPs, standardised methods are needed (i) to ensure the integrity of lipid-based products, (ii) to characterise their physico-chemical properties, (iii) to understand their behaviour in complex biological medium, and (iv) finally to follow nanoparticle biodistribution and biotransformation *in vivo*.

Objectives

This project aims to develop traceable measurement methods for the characterisation of innovative nanotherapeutics and associated RM candidates, focusing on synthetic lipid-based nanoparticles, e.g., liposomes and LNPs-RNA, and MONPs. The specific objectives are to:

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

1. Develop RM candidates for synthetic lipid-based and metal oxide nanoparticles and to measure their chemical composition, particle size distribution, polydispersity and particle concentration with a controlled uncertainty using existing methods.
2. Develop and harmonise traceable methodologies for measuring: a) particle size and concentration of small (<10 nm) nanoparticles and agglomerated or aggregated non-spherical objects, b) lipid composition and structural integrity of lipid-based nanoparticles, and c) nanoparticle surface properties, including the amount, chemical composition, and homogeneity of the surface coating.
3. Develop and harmonise robust and efficient sample preparation methods for the measurements of the nanoparticle stability and their biotransformation in biological matrices, and to minimise matrix interferences. Fractionation methods will be used, including size exclusion chromatography (SEC), field flow fractionation (AF4) and ultracentrifugation (UC) that are used to separate nanoparticles from free proteins in plasma, reach a demonstrated recovery of the analyte of interest above 70 %, as required by ISO/TS 21362:2018 and CEN/TS 17273:2018. Additionally, to evaluate if repeatability/reproducibility target identified in ISO/TS 21362:2018 is fit for purpose.
4. Improve correlative methods and model tissue phantoms to measure nanoparticle uptake and distribution in single cells and tissues associated to their biodistribution profile, safety, and efficacy. This includes using a combination of complementary techniques (e.g., MS, single cell ICP-MS, EM, Raman- and fluorescence-based approaches) with the aim to reduce the uncertainty in the detection, localisation, and quantification of nanoparticles in single cells and tissues. The developed methods, RM candidates and model tissue phantoms to be consolidated through the performance of an interlaboratory comparison.
5. Facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, accredited laboratories), standards developing organisations (e.g., CEN/TC 352-Nanotechnologies, ASTM E56, ISO TC 229), VAMAS TWA 2 and TWA 34 and end users (e.g., the pharmaceutical industry, regulators, clinicians, nanomedical product manufacturers, nanomedicine research community).

Progress beyond the state of the art and results

Objective 1: RM candidates for synthetic lipid-based and metal oxide nanoparticles.

In this project, NMIs are collaborating with industrial stakeholders to develop a library of RM candidates representative of nanotherapeutics. The library includes:

- (i) Citrate and dextran coated iron oxide (Fe_xO_y) and hafnium oxide (HfO_2) formulations characterised by small particle sizes (constituent particle core <10 nm) or aggregated sub-populations;
- (ii) Onpattro-like LNPs and Moderna-like LNPs encapsulating mRNA and siRNA;
- (iii) PEGylated and not PEGylated liposomes loaded by different active pharmaceutical ingredients (doxorubicin, siRNA, mRNA) and with different surface charges;
- (iv) Fluorescent multi-element nanoparticles such as NaYF_4 and $\text{NaGd}_{1-x}\text{Y}_x\text{F}_4$ doped with Yb(III) and Er(III) as model systems for correlating and comparing elemental and optical methods for measuring nanoparticle (NP) uptake and distribution in single cells and tissues on the same formulations;
- (v) Amine-modified mesoporous silica nanoparticles (~100-150 nm); as model systems for the exploration of the measurement capabilities of certain surface-analytical methods

Stability studies of first NP samples have been started and are running to provide the timely basis for NP selection and storage conditions. The most promising test materials and candidate RM will be selected for stability and homogeneity testing. At the end of the project, a roadmap towards certification and commercialisation of these materials will be derived. All materials produced in the project will be used to advance the methodological state-of-the-art for measurement.

Objective 2: Methods for measuring a) particle size and concentration of small nanoparticles and of agglomerated or aggregated non-spherical objects, b) lipid composition and structural integrity of lipid-based nanoparticles, c) nanoparticle surface properties

The project is progressing beyond the state of the art in this objective by validating the use of traceable methodologies, including small-angle X-ray scattering (SAXS) and atomic force microscopy-scanning electron

microscopy -energy-dispersive X-ray spectroscopy (AFM-SEM-EDX) hybrid microscopy approach, for the measurement of particle size and concentration of Fe_xO_y and HfO_2 NPs (<10 nm) and their aggregates, also advancing the approaches for data analysis to reduce the associated measurement uncertainty. Additionally, the project is providing a structured tier approach for the determination of the lipid composition, drug loading and for the structural properties of lipid-based formulations including (i) bulk techniques, e.g. advanced mass spectrometry (MS), calorimetry, capillary electrophoresis, Raman spectroscopy, SAXS, and (ii) innovative emerging particle-by-particle measurements such as cryo-time of flight secondary ion mass spectrometry (cryo-TOF-SIMS) and cryo-transmission electron microscopy (cryo-TEM), by evaluating the sensitivity, precision and robustness of selected protocols and performing a preliminary uncertainty budget determination. First samples for metal-oxide and lipid nanoparticles have been characterised using these techniques. Under this objective, the project will also evaluate the applicability of emerging methodologies for the characterisation of particle surface chemistry and coating, including the quantitative determination of the average coating mass by differential scanning calorimetry and thermogravimetric analysis coupled to MS, and the particle-by-particle coating homogeneity by cryo-TOF-SIMS.

Objective 3: Sample preparation methods for the measurements of the nanoparticle stability and their biotransformation in biological matrices, and to minimise matrix interferences

The work on the development of fractionation methods for selected NPs is well progressing: participants are optimising the established separation methods, including MD-AF4 and SEC, for the characterisation and separation of HfO_2 , Fe_xO_y , liposomes or LNPs-RNA from complex biological media (serum, plasma and blood). Notably, optimised separation methods employing MD-AF4 have enabled efficient separation of LNPs/liposomes from matrices, bypassing the needs for invasive extraction procedures. Current efforts focus on MONP separation optimisation, analysis in biological matrix, and nanoparticle stability evaluation. Encouraging progress is evident in the development of fractionation methods for NPs, achieving target recovery thresholds required by available standards (ISO/TS 21362:2018 and CEN/TS 17273:2018) and ensuring comparability across institutes despite differing hardware and methodologies.

Objective 4: Methods and model tissue phantoms to measure nanoparticle uptake and distribution in single cells and tissues

The project is developing tissue phantoms systems based on gelatine and hydrogel technologies that are spiked with a known amount of HfO_2 , Fe_xO_y , fluorescent multi-element NPs, and fluorescent LNPs-RNA. Those materials serve altogether as RM candidates for particle localisation, quantification and uptake in solid tissues. The tissue phantoms under development will be used for evaluating method sensitivity, precision and robustness, as well as develop standard operating procedures (SOPs) for a range of complementary methods to identify, localise and quantify NPs correlatively, and providing the basis of an external (future) ILC for the evaluation of the associated measurement uncertainty.

Outcomes and Impact

The project has actively engaged its community by hosting notable events like co-sponsoring "International Standardisation Roadmap for Nanomedicine" and organising the first METRINO workshop during the NME23 conference. These gatherings fostered collaboration among various stakeholders, including industry professionals, characterisation experts, standardisation committees, European Pharmacopoeia representatives, and metrology institutes to discuss key concerns related to metrology, standardisation in nanomedicine and the need for a coordinated approach. As an outcome of community feedback gathered during these engagements, Metrino is focusing on educational actions such as expanding accessible resources through their digital communication channels and organising webinars like 'Standardisation and Validation made simple'. By targeting professionals, students, and lab technicians with this disseminated knowledge on advanced metrology techniques, standardisation processes, best practices, and common pitfalls in nanomedicine development, Metrino is dedicated to fostering a more unified and collaborative effort within the industry. To support this endeavor, Metrino has designed and launched (in early March 2023) a dynamic website (<https://metrino.eu/>), which provides not only the traditional description of the project's vision, missions, expected outcomes, results, publications, and deliverables but also features a dynamic list of news and events. Additionally, it offers a wide range of useful resources covering topics such as Nanomedicine, Regulatory Guidelines, key definitions, Metrology for Nanomedicine, SOPs, and Standards, as well as Reference Materials for Nanomedicine. Furthermore, Metrino is actively leveraging social media channels created for the project to reach and engage with the broader nanomedicine and metrology communities. In summary, Metrino has

started to demonstrate unwavering commitment to education and collaboration in the field of nanomedicine and metrology, providing accessible resources and fostering exchanges among industry stakeholders.

Outcomes for industrial and other user communities

This project's work and results on the development of reference materials and validated protocols will support industry in the design, characterisation, regulatory evaluation, and clinical translation of innovative nanotherapeutics. Such standardised methods will also provide knowledge about the structure-function relationship of the nanomaterial. This knowledge will provide confidence for regulatory acceptance and improving quality control methods. The understanding gained will be directly exploited by the industrial participants involved in the project in their exchange with regulatory agencies and by adopting the validated protocols for the characterisation of their formulations under development for their release. The uptake of the developed protocols and RM candidates, and alignment with industry beyond the consortium has been promoted through early engagement with additional industrial end users belonging to (i) the pharmaceutical industry and the medical device industry, (ii) SMEs that are members of the main European nanomedicine associations and (iii) instrument providers. Importantly, the ETPN (European Nanomedicine Technology Platform) is leading the impact work package, addressing the whole European nanomedicine community, and benefitting from its well-established network and methodology- for community building and common strategic thinking. All target groups of stakeholders have been invited to join the Stakeholder Advisory Board. Additionally, to promote the uptake of the project's results by these communities, the consortium has invited these to two workshops organised by the consortium i) [NME23 Satellite event MetrINo workshop](#) "Advancing on characterisation and standardisation methods: the regulatory needs and the industrial perspective"(Liverpool, June 22 2023) and ii) [The international standardisation roadmap for nanomedicine workshop](#) (Paris, 13 November 2023). The consortium will continue to engage them in future events, including workshops, webinars and dedicated events.

Outcomes for the metrology and scientific communities

The project is expanding the measurement capabilities of the NMIs involved in the consortium to provide preclinical, regulatory, and quality control services at the highest metrological level. Collaborations between NMIs, academia and industrial companies within the consortium is supporting the use of the created metrological infrastructure. The project additionally supports academia and several on-going EU projects by (i) providing SOPs, guidelines and templates for data reporting for less mature measurement methods and (ii) moving more advanced methodologies towards standardisation. To promote the uptake of the project's results by this community, the project is organising in-person workshops, webinars and high-level meetings between stakeholders all along the value chain of nanomedicine translation to the clinic.

Outcomes for relevant standards

The consortium is actively disseminating the outcomes of the project to national standardisation organisations, to standardisation committees, e.g., ISO/TC 229, CEN/TC 352 and ASTM E56, to the VAMAS Steering Committee, and to the Nano working party of the EDQM. Moreover, the consortium is closely in contact with the CCQM Task Group on Particle Metrology. Metrino is initiating targeted networking actions and sharing information on specific initiatives among the different stakeholders belonging to existing metrology and standardisation networks, as already done in the "The international standardisation roadmap for nanomedicine workshop" organised in Paris, the 13rd November 2023. The project actively collaborates in drafting three ongoing standardisation projects focused on lipid-based NPs in ASTM E56.08 and ASTM E56.02. Furthermore, the project will initiate a nanomedicine roadmap with CEN/TC 352, and two new standardisation projects on MONPs and inorganic NPs, based on the validation of methods responding to Objective 2 and Objective 3. Finally, the RM candidates, model tissue phantoms, and results of the internal inter laboratory comparison (ILC) responding to Objective 4 will serve as a basis to initiate an external ILC study under VAMAS TWA 40 - Synthetic Biomaterials, that will run beyond the lifetime of the project.

Longer-term economic, social and environmental impacts

This project actively supports the translation of European nanomedical innovation to clinical application. It reinforces and extends cooperation of the European nanomedicine community to worldwide measurement experts, innovators, and regulators. It leverages previous public and private European investment in nanomedicine, notably the hundreds of million Euros committed by the EU in their research and innovation programmes on nanotechnology for the last 15 years and will accelerate and optimise the translation of innovation into advanced and safer therapies, available to European citizens as globally. By reducing the risks

of the nanotherapeutic development process, this project will actively contribute to the local creation and development of innovative European SMEs. This is an impactful response to the need expressed by EMA of more collaboration across the European regulatory landscape to improve the innovation environment and enhance patient access to new medicines in line with the EMA Strategic Roadmap to 2025. The project is strengthening the position of Europe in determining international policy, regulation, and the direction of standards committees related to medicinal products. Such leadership will contribute to the development of European and international standards directly relevant to EU centred activities. The project will support the work of EMA and European national and international regulators within the pharmaceutical sector, while also creating a framework of global cooperation across stakeholders that will boost confidence in innovation, attracting investment. The project aims to reinforce the cooperation of NMI with EMA, the U.S. Food and Drug Administration (FDA), and other international regulators in the pharmaceutical sector and support the translation of such cooperation to standard bodies and measurement expert communities in Europe and the world. The project outcomes will help ensure that Europe sustainably and enduringly engages in the medical innovation process and that European citizens and economies will benefit from these innovations. In summary, this project represents a unique chance to ensure Europe is a global leader in nanomedicine, leading to value creation, both in cost savings for the healthcare systems and job creation notably through the creation of specialised SMEs, benefiting from a whole nanomedicine-friendly ecosystem.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months
Coordinator: Robin Schürmann, PTB		Tel: + 49 30 3481 7114
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	8. CEA, France	-
2. BAM, Germany	9. Curadigm, France	
3. INRIM, Italy	10. ETPN, France	
4. LNE, France	11. Nanobiotix, France	
5. RISE, Sweden	12. nanoPET, Germany	
6. SMD, Belgium	13. OGSA, Italy	
7. TUBITAK, Türkiye	14. OVGU, Germany	
	15. SINTEF, Norway	
	16. UGent, Belgium	
	17. UniPV, Italy	
Associated Partners:		
18. Empa, Switzerland		
19. LGC, United Kingdom		
20. NPL, United Kingdom		



Publishable Summary for 22HLT05 MAIBAI

Developing a metrological framework for assessment of image-based Artificial Intelligence systems for disease detection

Overview

Image-based artificial intelligence (AI) systems for disease detection are increasingly being developed, and it is vital that these tools are robust and effective in heterogeneous clinical settings. To date, performance has been assessed in an ad hoc manner, as there are no approved guidelines for evaluation. Most studies have methodological weaknesses and results that are not comparable. A standardised and impartial framework for performance, generalisability, and suitability assessment of AI tools could address such needs, enabling a more efficient, reliable, and reproducible validation of image-based AI systems for disease detection. This project will use breast cancer screening as the exemplar, benchmarking AI tools on a large real-world database of mammographic images, with the aim of designing a metrological framework for AI assessment in diagnostics.

Need

AI has the potential to revolutionize healthcare systems, playing a key role in future clinical decision-making. The exponential increase in healthcare data over the last decade, as well as the fast-paced technology developments, have resulted in promising novel AI approaches for diagnostic applications and risk prediction. However, the adoption of AI in clinical settings remains restricted, mostly due to i) limited data quality, structure, and interoperability across heterogeneous clinical centres and electronic health records, ii) absence of robust validation procedures, iii) distrust of predictions and decisions generated by AI systems, and iv) lack of harmonised government proposals and consensus guidelines on steps for their adoption. One barrier that continues to prevent the use of AI tools in clinical practice is that the training and benchmarking of AI algorithms requires large datasets that cover the full range of both patient variability and measurement conditions, or bias can be introduced. Poorly trained systems could lead to misdiagnosis and lack of generalisability. To overcome this barrier, large medical imaging databases and infrastructures for data collection, sharing and custodianship are therefore needed. Focusing on radiological imaging, the evaluation and testing of AI products require a high-quality set of images and associated clinical information on the screened population. However, there is a strong heterogeneity of clinical data, in terms of quality, volume, patient demographics, imaging equipment and acquisition/processing procedures. Hence, there is a need for categorisation and integration of data based on clinically relevant subgroups and image acquisition key factors. From a more technical point of view, a clear methodology to benchmark the quality of predictive AI models (with relevant associated metrics) is essential if AI is going to be used in disease detection and risk prediction. In such applications, where high-stake decisions are frequently taken, lack of interpretability can undermine trust in AI models, which are typically seen as “black boxes”. In the realm of clinical practice, the availability of interpretation methods for explainable and traceable AI tools is therefore strongly needed.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: June 2024

Thorough and consistent validation of image-based AI systems for disease detection is fundamental, not only in terms of sensitivity and specificity, but also for the implementation in the clinical environment, where a technical integration and interoperability of AI tools would be required, making indispensable the design of a global, standardised, and impartial AI assessment framework.

Objectives

The overall objective of this project is to develop a metrological framework necessary to support standardisation in image-based AI systems for disease detection. Using breast screening as an exemplar, the performance of explainable and traceable AI tools will be analysed on a large real-world database of mammographic images, informing the design of the standardised assessment framework.

The specific objectives of this project are:

1. To develop a technical infrastructure to be able to query and extract the relevant data from medical imaging databases, such as the OPTIMAM Mammographic Image Database (OMI-DB). To establish a methodology for centralised and common metadata indexes, creating an open-source middleware for translation of metadata from different imaging databases.
2. To identify image acquisition key factors and population subgroups and use these to categorise the clinical data into subsets, determining where there is sufficient data for training and validation of AI tools for disease screening. To develop a methodology to generate synthetic data derived from physics-informed models and data augmentation techniques based on measurement knowledge.
3. To use explainable and traceable AI tools for disease screening, providing the capability to train and retrain the tools as necessary. To benchmark the AI tools in terms of prediction performance, robustness, fairness and uncertainty quantification, under at least three scenarios, including low versus high image quality data, validation for specific patient demographics, presence of machine-based artefacts and noise sources. To develop and validate methods for the explainability and interpretability of the trained AI tools.
4. To provide an AI validation toolbox for diagnostic imaging, to summarise the performance testing evaluations and to give recommendations for the assessment of explainable and traceable AI tools for disease screening, with a focus on understanding their generalisability and sensitivity to varying populations, manufacturers, image processing, and acquisition techniques. To use the recommendations to design a global, standardised, and impartial AI assessment framework.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (British Standards Institution, ISO/IEC JTC 1/SC 42 – Artificial intelligence), and end users (e.g., clinical stakeholders, manufacturers of medical and healthcare products, regulators).

Progress beyond the state of the art and results

Technical infrastructure for interacting with medical imaging databases (Objective 1)

In order to evaluate the generalisability of an AI tool, the medical imaging dataset used should cover the range of populations and imaging technologies that the AI tool will encounter clinically. There are currently relatively few large-scale medical imaging databases. Each of these databases contains images from a single country, along with the imaging technology and data storage used in that country. This can make it challenging for end users to identify data suitable for their task, as the data are stored using different methodologies. This project will overcome the above issues by establishing a methodology for centralised and common metadata indices. This will allow high-level investigation of disparate imaging datasets across Europe using a common open-source middleware layer.

Progress was made starting from the analysis of currently available large-scale open access databases of mammography images, VinDr-Mammo and CSAW-CC. These databases will be used alongside the one managed by RSFT, OMI-DB, which contains over 2.000.000 processed and unprocessed digital mammography images extracted from the UK National Breast Screening System. An agreement with the Dutch Breast Screening Programme is already active for additional image collection and use within the project.

Differentiation of clinically relevant subgroups in data and generation of synthetic data (Objective 2)

For the training and validation of AI tools in a healthcare context, it is important to have enough clinically relevant subgroups to ensure the tools are generalizable and unbiased. Often, the subgroups can be unbalanced and there is missing data for key clinical and/or measurement factors. This project will develop a methodology to differentiate the subgroups based on key factors using existing clinical imaging data and will also develop methodologies to generate synthetic data to supplement the missing subgroups.

Progress was made by specifying in the available datasets relevant image subgroups dependent on breast size and composition (fat/glandular tissue fraction), breasts that have undergone surgery, suboptimal breast positioning, and presence of implants, clips and medical devices. In parallel, subgroups dependent on acquisition parameters that can affect the image appearance have been identified, comprising mammography system brand and model, dose level, x-ray spectrum, type of compression paddle used, and image post-processing. To expand the datasets for AI tool benchmarking, synthetic data are being generated with a comprehensive strategy, which involves in silico modelling (i.e., computer simulations that replicate the entire mammogram acquisition pipeline), and advanced data augmentation techniques based on Neural Style Transfer approaches using CycleGAN and diffusion models. The synthetic data will also be used to establish a ground-truth framework for AI tool explainability.

Assessment of AI-based tools for breast cancer screening with mammography (Objective 3)

For breast cancer screening, which is the exemplar that this project will work on, AI tools are increasingly being developed to detect disease and make risk predictions from mammographic images, showing very promising results, but there are still methodological concerns around the assessment of these tools that mean there is still a lack of wide-scale adoption in the clinic.

Progress was made by defining prediction tasks and associated performance metrics of high clinical relevance for breast cancer screening. In parallel, relevant AI models for the selected prediction tasks have been identified, to start the process of training and retraining on the selected image subgroups in a systematic manner. In this way, a thorough evaluation of the AI tools can be carried out, providing specific working examples for the assessment framework development.

Interpretation methods for explainable and traceable AI tools (Objective 3)

A clear methodology to benchmark the quality of predictive AI models that inform clinically relevant decisions is essential for AI to be used in clinical settings. This project will define and implement a taxonomy of metrics covering relevant dimensions of model quality that, together, ensure that the model is fit for purpose and trustworthy. Quantitative performance metrics will be calculated, and model quality will be assessed in terms of accuracy or prediction performance, ability to maintain high accuracy in a wide range of scenarios (robustness) and for diverse patient populations of interest (fairness), ability to produce understandable and interpretable predictions (explainability) and, potentially, ability to deliver well-calibrated confidence/credibility intervals of the predictions (uncertainty quantification).

In applications where important decisions are frequently taken, like in healthcare, lack of interpretability in predictive models can undermine trust in those models, which are typically seen as “black boxes”. The use of so-called “explainable AI” (XAI) tools is therefore strongly encouraged, when developing clinical decision-support systems. However, formal requirements for XAI methods are lacking and existing approaches are insufficiently validated, preventing them from being useful for actual quality assurance purposes as needed by medical applications. To overcome such limitation, this project will develop a framework to define a notation of correctness of XAI methods and to formally verify the correctness of XAI tools for mammography, using carefully selected ground-truth data (e.g. synthetically generated).

To this aim, progress has been made with the preparation of a questionnaire about the expectations and understanding of AI model application in clinical diagnostics, to arrive at the definition of “explainability”, as it is perceived by different groups. The groups selected by the consortium comprise AI model end-users (radiologists, clinicians), AI model developers, scanner manufacturers, regulatory entities, and associations of patients.

Design of global, standardised and impartial AI assessment frameworks (Objective 4)

The challenges associated with the safe implementation and deployment of AI in healthcare are clear, and government initiatives and guidelines demonstrate that it is a priority worldwide. The USA Food and Drug

Administration (FDA) recently published an AI-based Software as a Medical Device action plan, where supporting regulatory science effort on the development of a methodology for the evaluation and improvement of AI algorithms is one of their main goals. The European Joint Research Centre (JRC) recently published a Science for Policy Report on AI in Medicine and Healthcare, where they highlight the lack of tests, benchmarking, and evaluation processes as one of the issues delaying the implementation of AI systems in healthcare. Overall, guidelines on the regulation of AI technologies include high-level directions, but not specific guidance on the practical steps in AI evaluation and in the development of reliable assessment frameworks. This project will develop a standardised and impartial assessment framework that will enable more efficient, reliable, and reproducible validation of image-based AI systems for disease detection, using breast cancer screening with mammographic images as the exemplar. Specifically, this project will provide an accessible and operational AI validation toolbox for diagnostic imaging, and give, based on the performance testing evaluations, recommendations for the assessment of explainable and traceable AI tools for disease screening, in line with the current regulatory guidelines.

Outcomes and impact

Several dissemination and communication activities are ongoing, including the curation of project website (<https://www.maibaiproject.eu/>) and social media channels like LinkedIn, as well as forthcoming presentations at the *International Workshop in Breast Imaging*, the *European Congress of Medical Physics*, and the annual general meeting of the *European Metrology Network for Mathematics and Statistics* (EMN Mathmet). A stakeholder committee consisting of 13 members from 6 European countries has been established and will support the project in different fields of expertise, comprising industrial and certification areas, clinical and medical quality assurance areas, and research and academic areas. A first stakeholder workshop was organised in May 2024, to finalise the standardisation processes required for the management and categorisation of clinical data for AI application in the medical field. Useful feedback was provided by TÜV SÜD about the current global regulatory framework, and by the Oxford University Hospitals NHS Foundation Trust, about the opportunities for deploying AI in screening, and the need for monitoring at scale and for systematic evaluation. The invited stakeholders also addressed the consortium on what is expected and what is understood from AI model applications in clinical diagnostics, towards the definition of the fundamental concept of AI explainability.

Consortium members are actively taking part in standards and technical committees, to disseminate the outcomes from the different activities of the project, and provide feedback for the establishment of a regulation framework on AI application in medical diagnostics. Engagement has been established with the American Association of Physicists in Medicine, the UK National AI Standards Hub, the ISO/IEC JTC 1/SC 42 – Artificial intelligence, and the TC-IM working group “Metrology for Digital Transformation” (WG M4D).

Particular care has been also devoted to the training of technical staff, with the delivery of several training courses, on image acquisition key-factors and image processing in mammography, metrology for AI, as well as on project key-instruments, like the medical image database OMI-DB and the customizable platform for curating medical data SATORI, engineered by FhG.

Outcomes for industrial and other user communities

The standardised and impartial assessment framework developed in this project will enable more efficient, reliable, and reproducible validation of image-based AI systems for disease detection. This in turn will result in the scalability of AI systems for disease detection, enabling the reliable and safe use of AI in healthcare. More broadly, such a framework will provide a way for the AI-tech and digitalization industry to safely develop and implement their products, and for health service providers to build the trust needed to use them, giving a level playing field for competition and innovation in this key new technological arena. The consolidation of AI tools for medical application, as pursued by this project, will boost healthcare technologies, pushing the integration of diagnostic equipment with AI platforms or the use of AI-based software as a standalone device for both detection and diagnosis, facilitating clinical analysis automation.

The strong interest of the industrial community towards the project is demonstrated by the presence in the stakeholder committee of medical device manufacturers, like FUJIFILM Europe Healthcare GmbH, as well as representatives from certification and quality assurance areas, like TÜV SÜD.

Outcomes for the metrology and scientific communities

The complexity of healthcare, compounded by the user- and context-dependent nature of AI applications, calls for a multifaceted approach beyond the traditional evaluation of AI. This project brings together data science domain-specific expertise, in silico modelling, clinical research, access to medical data, and AI-based digital technologies for healthcare. These are combined with metrological expertise in uncertainty quantification, key comparison data evaluation and standardisation. Such commitment is well-aligned with the strategies of the EMN Mathmet, of which most of the National Metrology Institutes (NMIs) involved in this project are members. Within the EURAMET community, the consortium also receives the endorsement from the TC-IM WG M4D, for the perspective of a European vision on digital transformation in metrology.

Moreover, the project is contributing to the building of an Open Access culture, through the implementation of the FAIR digital data principles. This enables us to impact on the promotion of the SI Digital Framework, as strongly recommended by the International Committee for Weights and Measures (CIPM).

Outcomes for relevant standards

Consortium members are actively participating in many standards and technical committees, like the International Atomic Energy Agency (IAEA) Update Human Health Series No 17, where a short chapter on AI systems in mammography and the need for their evaluation is under preparation, including feedback from the project. Important outcomes for relevant standards are also expected from the engagement with the American Association of Physicists in Medicine, and specifically with “Breast X-ray Imaging” subcommittee, and task groups 245 “Tomosynthesis Quality Control” and 419 “Basic Performance Testing of Contrast-Enhanced Mammography Systems”. Another relevant result is the endorsement from the UK National AI Standards Hub, which intends to propose the project as a case study for risk management.

Finally, the work developed in this project will provide specific guidance on the practical steps for AI evaluation in healthcare, being in line with the programmes of high-level standards bodies, such as the ISO/IEC JTC 1/SC 42 – Artificial intelligence.

Longer-term economic, social and environmental impacts

Benefits from this project are expected in different economic sectors, including healthcare and medical device industries, as well as companies specialised in digital technologies and data platforms. The growing datasets of patient health-related digital information, increasing demand for personalised medicine, and the rising demand for reducing care expenses are some of the major driving forces of the healthcare market growth. Looking specifically at the diagnostic application of AI, the market size was valued at € 576.3 million in 2021 and is projected to grow at a CAGR of 26.3% from 2022 to 2030.

By developing a robust infrastructure for the management of cancer screening data, and by providing high-quality training data and explainable AI-based tools for clinical interpretation, this project could concur to the future scalability of low-cost screening programmes. This will directly impact on the quality of life, with the possibility to treat diseases at early stages, improve the monitoring of their evolution and address therapy strategies in a more personalised way. As longer-term effects, increased survival rate and reduced costs for national health systems and the society are expected, considering that the total cost for cancer treatment and its management in Europe is € 199 billion/year. Supporting the widespread adoption of AI could help alleviate capacity shortfalls, and increase the viability of screening programmes in the developing world.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2023, 36 months
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Internal Beneficiaries: 1. INRIM, Italy 2. CMI, Czechia 3. DFM, Denmark 4. IMBiH, Bosnia and Herzegovina 5. IPQ, Portugal 6. PTB, Germany	External Beneficiaries: 7. FhG, Germany 8. ISS, Italy 9. LRCB, Netherlands 10. UL, Slovenia	
Associated Partners: 11. NPL, United Kingdom 12. RSFT, United Kingdom		

Publishable Summary for 22HLT06 GenomeMET

Metrology for genomic profiling to support early cancer detection and precision medicine

Overview

Cancer is a major burden on European society. Advances in genomics, driven by technologies such as Next Generation Sequencing (NGS) are transforming cancer care, enabling earlier and more accurate diagnosis, guiding therapy selection and driving development of targeted therapies (precision medicine), which improves patient outcomes and health system effectiveness. However, the quality and comparability of genomic profiling currently varies significantly and development of standards and metrological means to support the field are in their infancy. This project aims to address these needs by applying metrological principles to develop reference measurement systems (RMS) to support cancer genomic diagnostics in compliance with the In-vitro Diagnostic Device Regulation (IVDR EU 2017/746).

Need

Cancer is one of the most significant challenges for European societies and healthcare systems, being the second largest cause of death with more than 1.9 million deaths per year. Horizon Europe's Mission on Cancer has identified earlier diagnosis and implementation of precision medicine as key priorities for reducing deaths, improving health and the cost-effectiveness of health systems.

Precision medicine relies on molecular characterisation of a patient's disease, with genomic profiling central to new treatment models, enabling earlier and more accurate diagnosis/stratification and guiding targeted therapies. The EU Beating Cancer plan recommends genomic profiling for all cancer patients, with the "Cancer Diagnostic and Treatment for All" initiative improving access to new genomic diagnostics.

High quality genomic testing using technologies such as NGS and liquid biopsies is vital for successful implementation of precision medicine. However, NGS relies on complex multi-step workflows to simultaneously analyse large numbers of genomic variants. These are susceptible to major and poorly understood sources of uncertainty, resulting in significant variability and a current lack of comparability thereby impacting patient care and hindering wider implementation.

The standards and RMS to support assay validation and Quality Assurance (QA), including reference measurement procedures (RMP) and higher order methods, i.e., high-accuracy methods with low uncertainty that can be used as reference methods or for value assignment of reference materials, SI-traceable reference materials (RM) and measurement uncertainty (MU) guidance have yet to be established and are urgently needed to support new test development and approval under IVDR EU 2017/746 and implementation by clinical laboratories accredited to quality standards such as ISO 15189 or ISO 17025.

Developing and establishing novel metrological concepts, capabilities and RMS for genomic profiling will require a large-scale, multi-disciplinary and coordinated approach in collaboration with key end-user stakeholders to achieve the collective goals.

Objectives

The overall objective of this project is to develop metrological capability and to establish metrology frameworks to improve quality and reproducibility of critical processes within genomic profiling workflows as well as RMS for high accuracy SI-traceable cancer gene measurement to improve comparability and support assay validation as required by the IVDR (EU) 2017/746.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: July 2024

The specific objectives are:

1. To demonstrate the application of Reference Measurement Systems (RMS) to support development, validation, and quality assurance (QA) and external quality assessment (EQA) of genomic IVDs in accordance with EU IVDR 2017/746, including i) the establishment of an initial baseline framework (using outcomes from Objectives 2, 3 and 4), and ii) demonstration of proof of concept using key cancer genomic profiling models (NGS).
2. To establish Reference Measurement Procedures (RMPs) for high accuracy (VCs < 20 %) SI-traceable (to N=1) measurement of key cancer biomarkers and higher order methods to measure critical Quality Control (QC) parameters within genomic profiling workflows to support genomic RMS development.
3. To develop and characterise Reference Materials (RM) and external quality assessment (EQA) materials for genomic profiling in line with ISO 15194, ISO 15711 and JCTLM, with SI-traceable reference values and sequencing datasets, and to use these to establish a framework for SI traceable value assignment and commutability assessment of reference and EQA materials to support genomic IVDs.
4. To develop a framework for determining the measurement uncertainty (MU) in quantitative genomic data and nominal output data in multiparametric genomic profiles.
5. To facilitate take up of the measurement infrastructure, methods and materials developed in the project by the measurement supply chain (via EMN TLM), standards developing organisations (e.g., CEN TC 140 and ISO TC 212), and end users (e.g., healthcare, and medical laboratories, IVD developers, genomics/cancer/pathology institutes, EQA providers, RM producers, instrument/reagent developers, regulators).

Progress beyond the state of the art and results

GenomeMET will progress the state of the art by initiating development of novel metrological concepts, RMS and standards needed to support analytical validation and QA of genomic profiling IVDs for cancer patients. This will help enable implementation of accurate, comparable, and traceable genomic profiling for improved diagnosis, targeted treatment, and management of cancer. Some progress has been made since the beginning of the project. This includes the following advances described in the “Progress beyond the state of the art” sections:

Objective 1: To develop and demonstrate the application of Reference Measurement Systems (RMS) to support development, validation, and quality assurance of genomic IVD.

Current state of the art

Global and European efforts are underway to develop guidelines and standards to support the validation and QA/EQA of genomic profiling. However, current guidance for genomic test validation and QA lacks routes for independent comparability and assessment of analytical performance criteria.

Progress beyond the state of the art

This project will develop traceable methods for assessing critical quality attributes of key NGS genomic profiling workflow steps such as NA isolation (yield and quality) from clinical samples (tissue and liquid biopsy from cancer patients and NGS library preparation (yield and uniformity of coverage) feeding into frameworks to support assay QA. To date, the project Consortium has prioritised clinical model applications, including molecular stratification (disease sub-type), minimal residual disease (MRD) testing, and advanced cancer treatment selection, has chosen cancer types of lung and colorectal cancer, and has defined and prioritized the Critical Quality Metrics (CQM) for Laboratory Workflow QA/QC and Assay Validation and related examinands and measurands in both pre-analytical and analytical phases, including fragment size distribution, sample purity, instrument performance, procedural consistency, and adherence to standardized protocol. Information of genomic methodologies, sample requirements, sequencing parameters and data analysis information for tissue and liquid biopsy sample workflows have been collected by an extended literature review was made also on the state of the art on the latest ISO international standards, guidance, scientific publications, and initiatives in the field of early cancer detection. A clinical sample-planning document has been finalized to summarise and guide sample collection sharing and secure storage within the project.

Objective 2: To establish reference Measurement Procedures (RMP) for cancer biomarkers, and higher order methods.

Current state of the art

To date, there is only one primary RMP for quantification of a single cancer genetic variant in JCTLM DB, which is limited in scope to synthetic DNA controls.

Progress beyond the state of the art

The project will develop RMPs for high accuracy and SI-traceable measurements of key cancer biomarkers, assessment of the performance of RMPs using contrived RMs as well as demonstrating the applicability of RMPs to support validation of genomic profiling workflows. It will also establish novel sequencing (NGS/Sanger) strategies/capabilities for orthogonal validation of genomic variant calls, and identity and purity certification of genomic RM/EQA materials.

To date, the project has identified biomarkers representing key cancer variants including KRAS, BRAF, PIK3CA by an extended literature review and collected, in newly created tables, several information on those relevant biomarkers for early cancer detection and on the relative NA amplification-based methods for their quantification, including digital PCR. In addition, the project has selected the digital PCR (dPCR) as the best methodology for RMPs development for cancer gene variant quantification and total DNA quantity/fragment size measurements and has identified human specific (reference) genes that could be used for determination of total DNA concentration, by a literature survey and stakeholder consultations. Furthermore, the project has reviewed sequencing approaches for development of RMPs for nominal properties and characterization of reference materials and has selected the high accuracy NGS methods as sequencing technology to evaluate its potential as RMPs.

Objective 3: To establish SI-traceable frameworks for the development and characterisation of Reference Materials (RMs) and EQA materials for genomic profiling.

Current state of the art

WHO International Standards and commercial contrived RM/QCMs are only available for selected individual cancer biomarkers. Higher order RMs currently only exist for germline materials and only sequence identity is certified. In addition, these materials lack traceability to higher order standards and may not be commutable because frameworks for assessing the commutability of genomic RMs have not yet been established.

Progress beyond the state of the art

This project will support the roll-out of improved/new EQA schemes for cancer genomic profiling through provision of reference values to support traceability and comparability across schemes. It will establish routes for assessing commutability of complex multi-analyte genomic RMs taking into consideration nominal (variant identity) and quantitative Variant Allele Frequency (vAF) properties and will develop novel cell/tissue-based RM formats. To date, the Consortium investigated the availability of test/control/reference materials relevant to the cancer models/applications and cancer biomarkers and several exhaustive and informative tables are now available. In addition, materials for the development and assessment of RMPs for biomarkers/variant types and total NA quantity/quality have been selected. The project also identified EQA schemes relevant to the selected cancer models/applications, genetic variants, and/or selected technologies. Areas where new EQA schemes are needed to support cancer genomic testing have been recognized and reported. In addition, a very useful survey on standardisation requirements for cancer genomic profiling has been prepared and sent to relevant Stakeholders (mainly EQA schemes participants): the feedback was received from 95 laboratories and has given to the GenomeMET Consortium important information on their priority for standardisation in genomic workflow, reference genes, guidelines, etc, within the EQA schemes to support cancer genomic profiling.

The Consortium has initiated to investigate the feasibility of developing new RM/QCMs for cancer models/applications, where RM/QCMs are not available. The development of a potential "novel cell-based RM" for enrichment and genomic analysis of CTCs in liquid biopsy samples is started together with the optimization of cell culture systems for the development of novel cell-based RMs. Even the development of a strategy for new EQA scheme(s) aimed at accommodating emerging cancer testing modalities such as liquid biopsies has been initiated and the production/development of EQA materials for the schemes, as well as prototype samples for new schemes has begun. Fruitful new discussions on commutability for NGS were carried out in the

consortium at the last M9 meeting, giving rise to the beginning of a report on commutability for genomic profiling.

Objective 4: To develop a framework for determining measurement uncertainty (MU) of genomic profiling

Current state of the art

Traditional MU approaches for clinical chemistry and genetic testing focuses on single analytes which are incongruent with multiparametric genomic testing.

Progress beyond the state of the art

This project will establish a robust framework using statistical approaches for assessing MU for multiparametric genomic profiling assays considering both quantitative (read count and vAF) and qualitative (sequence/variant identity) parameters. To date, the Consortium has made progress by reviewing statistical approaches for measurement uncertainty evaluation and sources of variation when working with multiparametric genomic datasets within genomic profiling workflows. Suitable ready-to-work-on datasets have been identified, reported and collected on the project database. The project has also initiated the compilation of information (meta-data) on the datasets to indicate the varying factors and the available output data, as well as a list of variants and additional variant information. Furthermore, the variation in the qualitative and quantitative output data related to the process of library preparation is under investigation.

The project has reviewed literature and software repositories to identify relevant bioinformatics pipelines and best practice guidance related to the cancer genomic profiling methods to be utilized in GenomeMET. In addition, the review of the availability of raw sequencing data files in the datasets identified within the project, has been initiated. Furthermore, the availability of matched test and reference datasets to be utilized for evaluating the qualitative accuracy of bioinformatic pipelines, as well as the availability of software capable of computing qualitative accuracy of genomic datasets, is being determined. Finally, the uncertainty in the output data associated with individual modules in a bioinformatic workflow, such as sequence alignment or variant calling programs, is currently under evaluation.

Outcomes and impact

Several key dissemination and communication activities were undertaken to promote the project. Engagement was established with 20 standard development organizations, including 17 international and 3 nationals, such as ISO and CEN, 3 industry working groups, and 1 regulatory body. Particularly, relevant standards committee meetings have been attended, among them ISO TC 212 on Clinical laboratory testing and in vitro diagnostic test systems and specifically meetings of WG4 on microbiology and molecular diagnostics and CEN TC 140 that specifies requirements and gives recommendations for next generation sequencing (NGS) workflows for in vitro diagnostics and biomedical research. The project was presented in 2 national and 3 international events through poster and oral presentations such as at the "Human and Medical Genetics Conference 2024" and at the "EMBL conference: Cancer Genomics". Additionally, 5 training course were conducted, such as one focused on statistical analysis, one interactive online course about applying digital PCR and measurement science to support early cancer detection and MRD and one invited seminar on Digital PCR and Measurement Procedure to Support Advances in Precision Medicine at the ELITech group, an international IVD developer company. To further enhance outreach, a project website (<https://www.genomemet.org/>) and a LinkedIn page (<https://www.linkedin.com/company/genomemet/>) were created and regularly updated. Dissemination efforts also included participation in discussions during meetings, the release of newsletters, utilization of social media platforms, and the publication of press releases.

Outcomes for industrial and other user communities

This project's outcomes support the implementation of precision medicine for cancer patients. It is envisaged that these will have impacts across multiple key stakeholder communities including, but not limited to:

- IVD developers - RMS will support the generation of enhanced performance validation data incorporating MU and metrological traceability, enabling genomic IVD developers to better demonstrate performance in line with the IVDR. This will lead to improved quality and comparability of IVDs and faster translation to market through more streamlined and consistent regulatory submissions.
- Clinical laboratories – Higher order methods and QC materials for monitoring key workflow quality metrics and performance will enable clinical laboratories to establish improved and standardised QA

frameworks, resulting in better quality and more comparable genomic profiling across laboratories and supporting accreditation (ISO 15189 or 17025).

- Healthcare providers – Frameworks for assessing analytical performance will enable healthcare providers to undertake improved Health Technology Assessments (HTA) of novel genomic IVDs, incorporating more robust data with defined uncertainties to support future test performance specifications and uptake of genomic profiling into health practice.
- RM producers – Frameworks for improved characterisation and SI-traceable value assignment of genomic RMs will enable RM producers to demonstrate metrological traceability and commutability in line with the IVDR and ISO 17511, leading to more streamlined RM development and a wider range of high quality RMs. A collaboration agreement with a major RM producer who is now actively working with the project and is involved in the Consortium meetings.
- EQA providers – Provision of SI-traceable reference values will enable EQA providers to demonstrate long term comparability and traceability of EQA materials and schemes, reducing reliance on arbitrary consensus values. This will improve robustness and quality of genomic EQAs, and support development of new schemes and harmonisation of EQAs in molecular pathology. In the first nine months of the project, the Consortium worked hard to plan two new EQA schemes which will be performed in the coming months.
- Drug developers will be able to undertake more streamlined development of targeted therapies through improved quality of genomic data from clinical trials, enabling more accurate selection of responders/non responders, leading to reduced development times, fewer failures, lower costs, and more effective cancer therapies.
- Clinical researchers will be able to generate more robust, reliable and reproducible genomic datasets, helping to address the current reproducibility crisis in clinical translational research, supporting faster translation of novel biomarkers to the clinic.
- Regulators – RMS and guidance for assay validation, incorporating metrological traceability, will inform IVD competent authorities /regulators / reference laboratories on performance metrics for genomic profiling assays, enabling more streamlined assessment of new IVDs and development of recommendations for implementation of genomic approaches in clinical practice.

Outcomes for the metrology and scientific communities

This project will provide a vehicle for joint activity, inter-laboratory comparisons, and knowledge sharing to support development of novel metrological concepts and capability for clinical genomics. Outcomes will support improved EU metrology infrastructure enabling provision of new RMS and measurement/calibration services allowing NMI/DIs to provide more reliable SI-traceable reference values and improving agreement between different laboratories worldwide. Outcomes include:

- Improved NMI/DI capabilities for quantification of cancer genomic biomarkers, quantification of total Nucleic acids and detection of panels of genomic variants, demonstrated through inter-laboratory comparisons. GenomeMET partners will be participating in a new CCQM study: K189 “Measurement of Single Nucleotide Variation (SNV) and Small Deletion in Cancer Biomarker of PIK3CA and EGFR.” This will allow to demonstrate cancer gene variants quantification capability, under development in GenomeMET, through recognized CCQM studies.
- Dissemination of case studies to advance development of metrological frameworks for multi-analyte clinical genomic profiling.
- Submission of new RMP for quantification of cancer genomic biomarkers and SI-traceable RMs to JCTLM database.

The metrological capabilities developed in this project will also support the wider clinical genomics sector (e.g., rare diseases and non-invasive prenatal testing (NIPT)) where Next Generation Sequencing (NGS) profiling is being applied and complement metrology development for other ‘omics sectors where multi parametric testing is needed, e.g., transcriptomics, proteomics, and metabolomics.

Outcomes for relevant standards

The RMS to support assay validation will enable IVD developers, clinical laboratories, and other end-users, e.g., EQA providers and RMs producers, to better comply with regulations and standards in the IVD field e.g., IVDR and ISO 15189, ISO 17025 and ISO 17511 through generation of more robust and comparable datasets incorporating metrological traceability and MU.

Higher order methods, i.e., high-accuracy methods with low uncertainty that can be used as reference methods or for value assignment of reference materials, e.g., dPCR and materials (RMs/EQA materials) will support stakeholder-driven standardisation initiatives, linked to GenomeMET, e.g., INSTAND-NGS4P project by providing the underpinning methods/materials required to assess performance.

Outputs from this project will be incorporated into relevant CEN TC 140 and ISO TC 212 standards in development for NGS and liquid biopsies through participant representation on drafting committees, and into periodic revisions of standards such as ISO 15193, ISO 15194 and ISO 20914.

Finally, proposals for new standards under CEN TC 140 or ISO TC 212 are expected during the lifetime of the project in order to support improved validation and QA of genomic profiling and accurate quantification of cancer gene biomarkers. To date, a new standard has been proposed under ISO TC 212 WG4 to support "NGS-based oncology applications" with GenomeMET partners as part of the Expert Drafting Team.

Longer-term economic, social and environmental impacts

Outputs from the project will support earlier cancer detection and implementation of precision medicine, through confident and valid uptake of genomic profiling. Cancer is the second largest cause of death in Europe, with more than 3.7 million new cases and 1.9 million deaths each year and carries an economic burden of €141.8 billion/pa (1.07 % of GDP). Earlier detection and genomics-guided targeted therapies with greater efficacy and less toxicity compared to traditional systemic therapies will significantly reduce healthcare costs and improve patient outcomes. High quality genomic testing will result in fewer diagnostic errors e.g., missed/incorrect diagnosis and support provision of the "right drug to the right patient at the right time" reducing the economic burden of cancer and allowing citizens to live longer and healthier lives.

The project's outputs will also support growth of the European IVD and oncology therapeutics markets, valued at 33 billion Euros/pa and 75 billion Euros/pa respectively, through more streamlined routes for approval of new companion and precision genomic diagnostics, and improved genomic data from clinical trials resulting in more accurate selection of responders and more streamlined development of novel targeted therapies.

Environmental impacts include a reduction in the use of medical tools/devices and diagnostic kits/ components through more accurate "right first time" testing. These components are often single-use plastic products, the disposal of which presents an environmental risk.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		36 months
Coordinator: Carla Divieto, INRIM Tel: +390113919971 E-mail: c.divieto@inrim.it		
Project website address: www.genomemet.org		
Internal Beneficiaries:	External Beneficiaries:	
1. INRIM, Italy	6. CEA, France	
2. LNE, France	7. FPO, Italy	
3. NIB, Slovenia	8. INSTAND, Germany	
4. PTB, Germany	9. MUG, Austria	
5. TUBITAK, Türkiye	10. UNITO, Italy	
Associated Partners: 11. BIO-RAD, United States, 12. GenQA, United Kingdom, 13. LGC, United Kingdom, 14. METAS, Switzerland, 15. MHRA, United Kingdom, 16. ULE, United Kingdom		

Publishable Summary for 22HLT07 NEuroBioStand Standardisation of measurements of neurodegenerative disease biomarkers

Overview

Neurodegenerative disorders (NDDs) affect over nine million Europeans and constitute a large economic burden to society. NDD biomarkers have transformed the research landscape by linking diseases to pathological processes and assisting drug development. NDD biomarkers improve the accuracy of diagnosis and prognosis with the use of non-invasive tools. However, their implementation in clinical practice is hampered by a lack of standardisation. This project will build on the International Federation of Clinical Chemistry (IFCC) programme to standardise biomarker measurements, harmonise measurements across assay manufacturers as well as develop and implement new biomarkers.

Need

One out of eight people in Europe is affected by diseases of the nervous system (Alzheimer's and Parkinson's disease, multiple sclerosis, epilepsy, brain tumours, paraplegia etc) with costs associated to this group of diseases corresponding to one third of the healthcare expense in Europe before the pandemic. Early and accurate diagnosis of NDDs is crucial for effective management of diseases and early identification of patients who could most effectively benefit from new treatments. The number of fluid biomarkers available for early diagnosis of neurodegenerative diseases is growing together with the rapid development of assays that have the potential to be routinely used in clinic. Translational research and metrology have a key role to play in this landscape.

While research in NDDs has significantly progressed in the last few years through the discovery of new biomarkers and the development of non-invasive sensitive assays implemented on automated platforms, large-scale implementation of these biomarkers in routine clinical settings necessitates standardisation. To date, most initiatives striving for standardisation of NDD biomarkers are focused measurements performed in cerebrospinal fluid (CSF), including Amyloid Beta 1-40 (A β 1-40), Amyloid Beta 1-42 (A β 1-42), total tau (t-tau) and Neuro Filament Light chain (NfL). To meet the need for minimally invasive assays, there is an urgent need to standardise measurements of NDD biomarkers in blood. Building a European infrastructure for NDD biomarker standardisation is of utmost importance to rapidly implement new NDD biomarkers in clinical practice. Due to the structural heterogeneity of these biomarkers, detailed molecular characterisation of the analytes requires metrology to define the measurand and develop adequate reference method procedures (RMPs) and certified reference materials (CRMs).

Tau hyper-phosphorylation is one of the main hallmarks of Alzheimer's Disease (AD) allowing the discrimination of this disease from other forms of dementia and the early identification of affected patients. Commercially available immunoassays can target specific phosphorylated epitopes, but there is a strong need for standardisation based on the establishment of reference ranges and clinical cut-off points. This is addressed in Objective 1. NfL is a biomarker of axonal injury released from neurons in CSF and in blood. Standardised measurements of this biomarker are strongly needed in urgent care and treatment units for patients experiencing head injuries, strokes or neurological disorders like Amyotrophic Lateral Sclerosis (ALS) and Alzheimer's disease. This project will address this need in Objective 2. Despite recent discoveries in

Report Status:
PU – Public, fully open

Publishable Summary

Issued: July 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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translational research that have led to the establishment of Tau hyper-phosphorylation and NfL biomarkers, there is still a strong need for additional biomarkers and several gaps in their development and implementation need to be addressed. GFAP, a biomarker of astroglial activation, has recently been proposed as a biomarker in AD and acute central nervous system (CNS) injury. In Objective 3, this project will analyse the requirements for clinical implementation of GFAP, by evaluating the feasibility for the establishment of prototype reference materials and reference methods. Neurodegenerative diseases, like AD and Parkinson's Disease (PD), are characterised by the accumulation of toxic aggregates of proteins in patient neurons or brain parenchyma. This project, in Objective 4, will use structural analyses of chemical cross-linking coupled to mass spectrometry and native mass spectrometry to define monitoring for protein aggregates the biological fluids.

Objectives

This project will develop a metrological research framework for standardising biomarkers of neurodegenerative diseases (NDDs), including Alzheimer's disease, dementia with Lewy bodies, frontotemporal dementia and Parkinson's disease, the fast implementation and commercialisation of promising assays for NDD biomarkers will be promoted through compliance to the EU IVDR 2017/746.

The specific objectives are:

1. To standardise the measurement results of phospho-tau (P-tau) in plasma. This will include the development of new metrological strategies addressing multiple phosphorylation sites in biological matrices. This will be achieved by developing candidate reference measurement procedures with a target uncertainty of less than 15 %. Prototype reference materials will be developed, and their commutability will be assessed through inter-laboratories studies enabling plasma P-tau measurements performed in clinical practice to be standardised.
2. To standardise the measurement of neurofilament light chain (NfL) in plasma or serum by establishing reference measurement procedures and developing prototype reference materials of which commutability will be evaluated. This will require defining the appropriate target analyte/measurand and establishing and validating traceability chain strategies to reach a limit of quantification (LOQ) of 0.5 pg/mL in blood derivatives with target measurement uncertainty of less than 15 %. Additionally, an LC-MS (Liquid Chromatography coupled to Mass Spectrometry)-based clinical assay will be developed and its correlation with immunoassays will be established.
3. To implement clinical measurement of the glial acidic fibrillary protein (GFAP) as an emerging biomarker candidate by developing an SI-traceable LC-MS/MS method in biological fluids. This will include the development of primary calibrators of well characterised purity with an uncertainty of less than 15 %. A feasibility study will be carried out to evaluate the applicability to patient samples.
4. To develop effective and fit-for-purpose metrological approaches to overcome the challenges in standardising NDD fluid biomarkers. This will include the development of new metrological strategies to address protein conformational states, post-translational modifications and uncertainty frameworks.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (EMN-TLM, JCTLM, ICHCLR), standards developing organisations (IFCC WG-BND, Diagnostic Devices Regulation 2017/746 (IVDR), ISO TC12, ISO TC212), and end users (e.g., clinical stakeholders, manufacturers of medical and healthcare products).

Progress beyond the state of the art and results

The consortium is making significant progress in standardising biomarkers for neurodegenerative diseases, focusing on P-tau, NfL, and an emerging biomarker, GFAP. These efforts involve developing reference measurement procedures, producing certified reference materials, ensuring their commutability (ability to behave as real patients' samples) and stability, and developing metrological strategies for the elucidation of protein conformational states in NDD.

Objective 1: Standardisation of P-tau Measurement Results

Recent advances in ultrasensitive assays have enabled the measurement of phosphorylated tau (P-tau) in plasma, which has become a promising biomarker for Alzheimer's disease (AD). The first step in standardising this biomarker is defining the measurand, focusing on specific P-tau isoforms, including P-tau181, P-tau217,

and P-tau₂₃₁. The consortium is employing an isotope dilution liquid chromatography-tandem mass spectrometry (ID-LC-MS/MS) reference measurement procedure (RMP). This involves the digestion of plasma P-tau with trypsin, yielding peptides with predictable sequences.

The development of peptide calibrators for the targeted P-tau isoforms and sourcing of a GSK3 β -phosphorylated recombinant Tau protein have been key steps. However, challenges arose due to multiple consecutive or closely located trypsin-cleavable sites near phosphorylated residues, complicating peptide sequence prediction. The consortium has worked on selecting peptide sequences and producing phosphorylated peptide calibrators, which were characterised for purity and mass fraction.

A primary calibrator, GSK3 β -phosphorylated recombinant Tau-441, was sourced and underwent impurity assessment and mass fraction assignment. The developed materials were sent to UGOT for compliance evaluation using an IP-MS method in plasma, with LNE and ESPCI also implementing this method and optimising various conditions.

The candidate RMP will certify P-tau concentration in pilot matrix-based reference materials. Discussions about potential formats of these materials include plasma pools, pools spiked with recombinant protein, and pools spiked with cerebrospinal fluid (CSF), evaluated for commutability. Assay manufacturers have been approached for the commutability study, with Charité collecting ethical approvals for clinical specimens.

Objective 2: Standardisation of Neurofilament Light Chain (NfL) Measurement in Plasma or Serum

Neurofilament light chain (NfL) has been established as a robust biomarker for neuroaxonal damage in various neurological conditions. A candidate primary calibrator was developed, and an RMP for biological fluids is under development, starting with CSF due to its higher NfL concentration. The CSF method, involving precipitation, trypsin digestion, and HPLC purification, will be optimised for blood.

Challenges included interferences in the sample matrix and reproducibility issues, particularly due to the oxidation of a methionine residue in one of the two peptides used for quantification. This was addressed by forced oxidation, and further optimisations in sample preparation are ongoing. The method will be transferred to serum, potentially including an immunoprecipitation step, and used to certify reference materials.

A plan for developing prototype reference materials for NfL is underway. Charité is obtaining ethical approvals for clinical samples, and the study will include freeze-drying tests for material stability and an additional commutability study with patients having different NfL ranges.

A clinical LC-MS method using immunoprecipitation is being optimised for sensitivity by CHUM, using highly specific antibodies provided by ADx. Once optimised, serum samples from patients will be analysed, comparing different cohorts and immunoassays.

Objective 3: Development of Clinical Measurement Procedures for Emerging Biomarker Candidates

Glial fibrillary acidic protein (GFAP) has been selected as an emerging biomarker for various pathological states. The preparation and characterisation of a candidate primary calibrator for GFAP have been completed by TUBITAK. VUmc prepared and characterised frozen blood pools for GFAP concentration, sending these to TUBITAK that will develop a method using immunoprecipitation enrichment with nano magnetic beads.

Objective 4: Development of Metrological Approaches for NDD Fluid Biomarkers

NEuroBioStand is exploring the use of chemical cross-linking and native mass spectrometry to understand protein conformational states relevant to neurodegenerative diseases like AD and Parkinson's disease (PD). Studies at LGC using HDX-MS revealed that NfL has conformational heterogeneity and adopts different conformations in various environments. Interactions with human serum albumin (HSA) were identified, and higher-order structures such as dimers and tetramers were observed.

LGC also analysed tau-441 and phosphorylated tau-441 samples provided by LNE using native and intact LC-MS analysis, identifying main phosphorylation forms and proteinaceous impurities. Crosslinking-MS revealed significant structural differences between Tau and phosphorylated Tau at PTB, with a new method developed for pair-wise network and cluster analysis of crosslinks.

Outcomes and impact

Key dissemination and communication activities

During this reporting period, significant effort was made to engage with stakeholders through social media and the organisation of a symposium titled “Biomarkers in Neurodegenerative Diseases” in Montpellier. In addition, the consortium has given presentations at 6 other international conferences. The project’s LinkedIn page is a key resource for disseminating project news, announcements, conferences, and events, with content also posted on the project website. Additionally, a newsletter inviting stakeholders to the Montpellier symposium was circulated. Information on the project has been presented to the following standards working groups and committees: CCQM-PAWG, IFCC-WG BND, IFCC SD-EC, EURAMET TC-MC.

AlzPath, an industrial manufacturer of the first blood-based pTau217 test for early Alzheimer’s diagnosis, recently signed a letter of agreement, strengthening its collaboration with the consortium.

Outcomes for industrial and other user communities

Standardisation of biomarker measurements will greatly benefit assay manufacturers by facilitating the transfer of their assays from research to clinical practice. NEuroBioStand’s consortium has approached the major IVD providers developing assays targeting P-tau, NfL and GFAP. Most of them have also supported a symposium organised by the consortium in Montpellier. Discussions have been engaged around the organisation of two commutability studies on P-tau and NfL planned for the second half of the project.

The pharmaceutical industry will also benefit from the availability of more accurate and reliable biomarker data. Recently, the anti-amyloid treatment Kisunla (donanemab) from Lilly, has been approved from FDA. This treatment, together with Eisai’s Leqembi, will constitute a new opportunity for patients living with dementia. At this purpose, NEuroBioStand will contribute to standardise blood-based biomarkers that are crucial in clinical trials and in the stratification of patients to evaluate their eligibility to the new treatments.

The development of the RMPs for NDD biomarkers in blood will also have an impact on the community of mass spectrometry providers and the consortium is planning to engage with this community.

This project, in line with the priorities of the EMN-Traceability in Laboratory Medicine, will engage with instrument manufacturers and underpin their regulatory approval by ensuring compliance with the in vitro diagnostic regulations (IVDR).

Outcomes for the metrology and scientific communities

Significant effort was devoted to engaging with the scientific community: the above-mentioned symposium in Montpellier was co-organised with the French Centers of Excellence in Neurodegenerative Diseases (CoEN, AVIESAN) targeting clinicians, academics, in vitro medical device providers, and patient associations. CHUM managed the practical organisation, and LNE was part of the organising committee. The entire consortium contributed to the scientific program. Over 100 participants attended in person, with additional online attendees. The project coordinator provided an overview of NEuroBioStand’s project, and 7 out of 18 speeches were given by NEuroBioStand participants, highlighting the importance of NDD biomarker standardisation and networking with existing projects and results. Four consortium posters were also presented. The event was sponsored by key stakeholders including Alamar Biosciences, Quanterix, Olink, Fujirebio, Siemens, Biotechnie, Roboscreen, and Lilly. The patient association “France Alzheimer” was also among the sponsors.

Outcomes for relevant standards

The project will impact several standards and guidelines. In particular the BIPM’s Consultative Committees for Amount of Substance: protein analysis working group (CCQM PAWG) was consulted: an overview of the project’s objectives and its progress beyond NeuroMET projects were given by the coordinator. Activities between the committees and the project will be aligned to improve the standardisation of units, biotechnology processes and laboratory medicine. NEuroBioStand’s consortium benefits from the tight cooperation with the IFCC-WG-BND, which is chaired by UGOT: LNE has introduced the project to the working group, that will act as the advisory board of the project. Additionally, UGOT introduced the consortium at “IFCC WorldLab 2024” in Dubai, emphasising the importance of metrology in the standardisation of NDD biomarkers.

Longer-term economic, social and environmental impacts

To date, two disease-modifying drugs against AD have been granted approval by the American Food and Drug Administration (FDA), and several other drug candidates are currently at different stages of clinical trials. In an

era when NDDs become treatable, it will be of paramount importance to identify patients at risk at an early stage, so that the right treatment can be administered before neurodegeneration has caused severe damage to the brain. In this context, fluid biomarkers will most likely play an important role as cost-effective, non-invasive tools for early diagnosis of NDD. The use of non-invasive, blood-based and widely accessible tools will reduce the recourse to imaging for large-scale screenings, thus limiting costs for the healthcare system. The standardisation effort carried out during this project could lead to the implementation of multiple assays coming from different companies for the same biomarker in a competitive perspective that will contribute to limiting the prices of assays on the market.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		October 2023, 36 months
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Project website address: https://projects.lne.eu/jrp-neurobiostand/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. LNE, France	4. Charité, Germany	9. ADx, Belgium
2. PTB, Germany	5. CHUM, France	10. JRC, Belgium
3. TUBITAK, Türkiye	6. ESPCI, France	
	7. UGOT, Sweden	
	8. VUmc, Netherlands	
Associated Partners: 11. LGC, United Kingdom		
Affiliated Entities: 12. CNRS, France (affiliated to ESPCI)		



Publishable Summary for 22IEM01 TOCK Transportable optical clocks for key comparisons

Overview

In recent years, significant progress with optical clocks has been achieved, such that they clearly outperform current primary standards of time and frequency. The currently established key comparison for time and frequency uses satellite-based techniques to provide international consistency with 10^{-16} fractional uncertainty. Optical fibre links between a few NMI laboratories in Europe are available and can enable clock comparisons with low 10^{-18} uncertainty, but these are limited by relativistic effects. To overcome these limitations and to compare optical clocks that cannot be interconnected via optical fibre links, this project will develop travelling frequency standards with performance exceeding the current state-of-the-art. The use of these transportable optical clocks (TOCs) as frequency standards will be evaluated by the project and their feasibility for use in future key comparisons will be demonstrated.

Need

The fundamental properties of atoms provide characteristic microwave or optical frequency references used in atomic clocks to realise the most precise measurement devices available today. Within the SI system of units, the realisation of the unit of time with Caesium atomic clocks plays an essential role, as the unit second is contained in the definition of 6 of the 7 base units via the defining constants. Having highly accurate, stable, and reliable reference frequency standards is a pre-requisite not only for the SI System of Units, but also for many everyday technologies that rely on precise time keeping such as banking transactions, communication, and navigation.

Due to the higher reference transition frequency, highly precise optical clocks have made great progress with a variety of different reference systems with neutral atoms and single ions. The established methods for international key comparison in time and frequency currently use satellite-based techniques. However, satellite-based techniques have a clear limitation for comparisons of these high-performance clocks and are unable to take full advantage of the future redefinition of the unit of time. To overcome these limitations, travelling frequency standards with performance exceeding the current state-of-the-art need to be developed, evaluated, and tested for use in future key comparisons. This is particularly urgent given the growing needs in global communication and navigation.

TOCs also need to be developed to provide accurate and stable frequency references outside NMIs and DIs for example at specialised research facilities, for geodetic base stations or in future telecommunications and navigation systems. Thus, the research in this project will address the need for advanced techniques for providing traceability for measurements to the users of metrology services.

Objectives

The overall goal of this project is to develop an integrated European metrology infrastructure for the development and deployment of highly stable and accurate TOC systems. The specific objectives of the project are:

1. To develop and to demonstrate the performance of commercially unavailable components of TOC systems (e.g., ultra-stable laser, optical bench for atom/ion cooling, trapping and interrogation, UHV physics package for atom/ion clock) capable of operation within 5 days after transportation.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



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Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

2. To develop TOCs that demonstrate short-term frequency instabilities below $5 \times 10^{-15}\sqrt{\tau(s)}$ and a systematic uncertainty equal or below 5×10^{-18} .
3. To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.
4. To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs), international metrology committees (e.g. CIPM Consultative Committee for Time and Frequency (CCTF)) and end users (research facilities in geodesy, space and physics, telecommunications and aerospace enterprises, scientific and precision instrumentation manufacturers).

Progress beyond the state of the art

This project builds upon the achievements of previous EMRP and EMPIR projects, most recently 18SIB05 ROCIT and 20FUN01 TSCAC. In 20FUN01 TSCAC fundamental aspects of the future realisation of composite optical clocks based on two atomic species is being investigated and in 18SIB05 ROCIT the robustness of established optical clock systems was improved, and their application for the steering of international timescales was demonstrated. This project is building upon these results and focussing on the development and deployment of highly stable and accurate TOC systems and investigate their use in future key comparisons for time and frequency.

To develop and demonstrate the performance of commercially unavailable components of TOC systems

TOCs have special requirements for their components; they need to be capable of withstanding transportation and thus have higher demands on weight, size and power consumptions, whilst a similar performance to their stationary counterparts in a laboratory environment is needed. In particular, operation shortly after transportation (i.e. within 5 days) is often needed for TOCs. Some of the required components for TOCs have been made commercially available, however, so far commercially unavailable components include ultra-stable laser, optical benches for atom/ion cooling, trapping and interrogation and UHV physics packages for atom/ion clock. These components not only need developing but their proper operation within 5 days after transportation also needs to be verified. This project is going beyond the current state of the art by developing and verifying such unavailable components for TOCs. In this way, key components will be made available for the first time for prototypes and can be used for later commercialisation by industry stakeholders.

To develop TOCs that demonstrate short-term frequency instabilities below $5 \times 10^{-15}\sqrt{\tau(s)}$ and a systematic uncertainty equal or below 5×10^{-18}

So far only, a few TOC prototypes have been realised worldwide, with the most advanced system realised in Japan demonstrating mid 10^{-18} uncertainty. In Europe, first prototypes of TOCs have been realised, but their uncertainty has been larger than 10^{-17} so far. Within this project, new systems are being developed and existing TOCs improved with the aim of reaching frequency instabilities below $5 \times 10^{-15}\sqrt{\tau(s)}$ and systematic uncertainties equal or below 5×10^{-18} . The project is going beyond the state of the art and focussing on the development of physics packages that enable operation with low frequency instability as well as the investigation of systematic frequency shifts for the specific operational conditions of TOCs. This work will increase the number of available TOCs in Europe and significantly strengthen Europe's measurement capabilities.

To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.

Only a handful of measurements involving TOCs have been reported in current literature, and only in a single case has an uncertainty below 10^{-17} been achieved. This clock comparison was against another system that was almost identical meaning that some systematic shifts were common-mode. To prevent unobserved

systematic effects, within this project, TOCs are being evaluated and compared to stationary systems that differ significantly in their design from the TOCs. In this way, a detailed assessment of the frequency stability and the systematic uncertainty of the TOC can be performed. In addition to this, the project will investigate the limitations related to transportation, by repeating procedures after real or simulated transportation. This repeated evaluation will enable the compilation of guidelines for the re-evaluation of operation parameters of TOCs after transportation and how TOC performance can best be retrieved after transportation.

To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.

Across Europe a few NMIs and DIs are interconnected using dedicated optical fibre links that enable frequency comparisons with low 10^{-18} uncertainty, that is limited by relativistic effects. To overcome these limitations and go beyond the current state of the art, this project will compare optical clocks that cannot be interconnected via optical fibre links and demonstrate the use of travelling frequency standards in future key comparisons in time and frequency. For these comparisons, the project will perform complementary measurements over existing fibre links in order to maximise the impact of each campaign and to mitigate the risk of a failure of the stationary clock system.

Results

Objective 1: to develop and demonstrate the performance of commercially unavailable components of TOC systems.

The project is currently developing commercially unavailable components including ultra-stable laser, optical benches for atom/ion cooling, trapping and interrogation and UHV physics packages for atom and ion clocks. As part of this, existing setups are being improved and new vacuum chambers have been designed. For ion-based clocks ion traps coating of the electrodes and for neutral atom clocks atom cooling is being investigated. For transportable clocks laser stabilisation is crucial, therefore, setups for this and their distribution has been prepared and will subsequently be set up.

Objective 2: to develop TOCs that demonstrate short-term frequency instabilities below $5 \times 10^{-15}\sqrt{\tau(s)}$ and a systematic uncertainty equal or below 5×10^{-18} .

The project is working on improving the loading and trapping conditions for ion-based clocks, in order to ensure reliable long-term operation. Furthermore, components will be combined to set up TOCs demonstrating the expected performance in a later part of the project. For existing clock setups, work is focussed on ways to improve both the instability and systematic uncertainty. While for reduced instability short preparation periods and long interrogation times are essential and have been focussed on by the project. The systematic uncertainty can also be reduced by an improved evaluation of the leading shift effects such as perturbing thermal radiation as well as other perturbing electric and magnetic fields.

Objective 3: To evaluate the TOCs by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the TOC for investigation of possible errors.

So far, the project has performed first comparisons between TOCs with stationary systems in order to assess the estimated uncertainty of the systems and to verify their instability. For an ion-based system an instability of $6 \times 10^{-15}\sqrt{\tau(s)}$ was observed and very good agreement with the stationary system. A much lower instability of below $5 \times 10^{-16}\sqrt{\tau(s)}$ was observed for a TOC based on neutral atoms in an optical lattice. These components not only need developing further but their proper operation within 5 days after transportation also needs to be verified. This project will go beyond the current state of the art by developing and verifying such unavailable components for TOCs. In this way, key components will be made available for the first time for prototypes and can be used for later commercialisation by industry stakeholders. Within the consortium the TOCs are currently being prepared for comparisons against between participants laboratory systems. This includes the setup of the necessary infrastructure at different participants laboratories.

Objective 4: *To demonstrate the feasibility of future key comparisons using TOCs as an alternative to established time and frequency key comparisons performed via satellite-based techniques.*

Currently, preparations are under way for the first clock comparison campaigns after transportation of TOCs. This includes (i) preparatory work at the involved participants, (ii) work on the optical fibre links that will enable an increase of the number of remote optical clocks and (iii) a discussion of data formats.

Outcomes and impact

The project has set-up a website at <https://www.ptb.de/epm2022/tock/> to promote the project to stakeholders. The project has also been promoted via 2 media articles by partner VTT <https://yle.fi/a/74-20051993> and <https://yle.fi/a/74-20059025>

In conjunction with the kick-off meeting of this project, a stakeholder workshop was held in hybrid format together with the EMPIR project 20FUN01 TSCAC. Presentations were given that demonstrated the outcomes from 20FUN01 TSCAC and the plans for this project 22IEM01 to approx. 50 participants from industry and the scientific community. The results of this project will be presented in a second similar workshop which will be held towards the end of this project.

Outcomes for industrial and other user communities

The techniques and hardware developed for TOCs within this project will benefit research groups and industrial organisations developing portable/transferable optical clocks for use in field applications. The outcome of the project may also lead to new ideas for improving the robustness of laboratory optical clocks. The clocks developed within the project will become role models for optical clock development at industrial stakeholders. A number of components for TOCs are commercially available, however, there are still many commercially unavailable components (e.g. ultra-stable laser with 10^{-16} fractional instability, optical benches for atom/ion cooling) and this project will develop verify these currently unavailable TOC components so that complete systems can become commercially available for applications including geodetic height measurements, synchronisation of telecommunications networks and future satellite navigation systems. Applications of such clock subsystems can also be extended by industry to other areas such as precision spectroscopy and quantum information processing. Moreover, industrial development of optical and electronic systems will be supported by via the project's production of good practice guidance on (i) the-state-of-the-art optical clocks and key technical aspects on the integration of optical clocks and (ii) optical clock time and frequency comparison techniques. Further to this the project has so far identified and involved 8 industrial stakeholders in project workshops and lectures and engage them via social media channels.

Outcomes for the metrology and scientific communities

This project will investigate new ways to perform key comparisons for time and frequency using highly stable and accurate TOC systems. The development and deployment of such new TOCs will improve the accuracy with which distant clocks can be compared and thereby supports the selection of suitable reference systems for a redefinition of the SI second, an essential contribution to fundamental metrology and to the long-term development of the SI system of units.

It is intended that a collaborator will be invited to project meetings to foster scientific knowledge exchange with the stakeholder community in the field of geodetic measurements. This will also be used to inform the consortia of the most recent advances in geodesy and potential use of clock comparisons involving TOCs. So far 11 key stakeholders from the metrology and scientific communities have been identified.

The project's results should also benefit fundamental physics, e.g., comparisons between optical clocks with verified uncertainties can be used to set limits on possible present-day variations in fundamental physical constants, to test the predictions of special and general relativity and to search for dark matter candidates.

The project's production of 2 good practice guides, will also benefit the metrology and scientific communities. Further to this the project will disseminate its outcome to the metrology and scientific communities via project workshops, lectures, conferences, open access publications and a summer school for young researchers.

So far, the project has engaged with the scientific community via 3 tutorials on (i) Optical clocks, (ii) Highly Charged Ion Clocks, and (iii) Quantum Logic Spectroscopy. The project has also supported an PhD thesis on 'A highly stable UV clock laser'.

The consortium has also presented the project 16 times (as posters or presentations) at conferences such as ICOLS 2023 (International Conference on Laser Spectroscopy), EQTC 2023 (European Quantum Technologies Conference), 9FSM 2023 (the 9th Symposium on Frequency Standards and Metrology) and IEEE IFCS-EFTF 2023 (Joint Conference of the IEEE International Frequency Control Symposium and the European Frequency and Time Forum).

Outcomes for relevant standards

The project has already been present to CIPM's CCTF Task force for the redefinition of the second SG1. The project investigates alternatives to the established key comparison for time and frequency, thus the main impact in standardisation will be through the CIPM's CCTF and its working groups; the Frequency Standards Working Group (WGFS), Working Group on Primary and Secondary Frequency Standards (WGSPFS) and Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT). The consortium is well represented on these bodies, where information on the project progress and outputs will be disseminated through presentations and reports. In particular, the project's report on the feasibility of future key comparisons using transportable optical clocks as an alternative to established time and frequency key comparisons performed via satellite-based techniques, is expected to impact the list of recommended frequency values maintained by CCTF's working groups.

Reports on the project outputs will also be presented to other working groups of the CCTF, such as WGSP, which is responsible for updating as necessary the international roadmap towards a future redefinition of the SI second. Further to this the project will provide input to EURAMET Technical Committee on Time and Frequency (TC-TF), which is responsible for the cooperative structure of time and frequency metrology laboratories in Europe.

Longer-term economic, social and environmental impacts

The longer-term impact of this project will result from the pivotal role of atomic clocks in the future revisions of SI units and in several growing technology sectors. The project's results will support the international metrological community in their decisions towards a future redefinition of the SI second. Improved techniques to compare atomic clocks and the development of TOCs are also relevant for technological applications, in sectors such as navigation, space, aerospace, telecommunications and energy networks. Further to this, TOCs have the potential to support future miniaturisation of payloads on onboard satellites and aerospace vehicles, and to support geodesy with cm-level precision and applications in climate research.

Project start date and duration:		1 May 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Associated Partner:
1. PTB, Germany	12. HHUD, Germany	17. BHAM, United Kingdom
2. BEV PTP, Austria	13. ISI, Czechia	18. NPL, United Kingdom
3. CMI, Czechia	14. LUH, Germany	
4. DFM, Denmark	15. UMK, Poland	
5. GUM, Poland	16. UvA NL, Netherlands	
6. INRIM, Italy		
7. LNE, France		
8. OBSPARIS, France		
9. ROA, Spain		
10. VSL, Netherlands		
11. VTT, Finland		



Publishable Summary for 22IEM02 DireK-T Dissemination of the redefined kelvin

Overview

The aim of this project is to take advantage of the kelvin redefinition using practical primary thermometry approaches for the dissemination of thermodynamic temperature. The kelvin redefinition in May 2019 initiated a comprehensive research phase for the realisation and dissemination of thermodynamic temperature to replace the ITS-90/PLTS-2000 scales currently in use. This project progresses beyond the state of the art, through: demonstrating dissemination of the kelvin from 4 K to 300 K; developing a robust framework for establishing traceability by primary thermometry; working towards the next generation primary thermometry to 700 K.

Need

The CIPM (International Committee of Weights and Measures) Consultative Committee for Thermometry (CCT) recommendation T1 (2017) stated that member state National Metrology Institutes (NMIs) “take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and *the mise en pratique* for the definition of the kelvin (*MeP-K*)”. In addition, the research needs for temperatures above ambient was highlighted by the CCT recommendation T1 (2021) that NMIs establish capability to determine the difference ($T - T_{90}$) between the thermodynamic temperature T and its approximation, the defined scale ITS-90 (T_{90}), above 400 K and, in so doing, establish the background capacity for dissemination of thermodynamic temperatures approaching 700 K.

The *MeP-K* allows for the dissemination of temperature either by thermodynamic means or one of the defined scales. However, many issues remain about how the two approaches interrelate and how to demonstrate the degree of equivalence. To facilitate disseminating thermodynamic temperature these issues need addressing.

The EMPIR JRP 18SIB02 Real-K project began the transition away from defined scales by establishing the capabilities to disseminate thermodynamic temperature at high temperatures >1235 K and low temperatures, particularly <5 K. This project’s research, building on the achievements of EMPIR JRP 18SIB02 Real-K, addresses the high-level metrology needs stated by CCT, ensuring that thermodynamic temperature can be realised and disseminated to room temperature and beyond. The project includes a wide range of NMIs ensuring the developed approaches are appropriate for NMIs at different stages of development.

Objectives

The overall objective of this project is to establish the capability to disseminate thermodynamic temperature from 4 K to ~300 K, which requires an internationally agreed framework to demonstrate that thermodynamic temperature dissemination is reliable, as well as to enable thermodynamic temperature dissemination above 300 K.

The specific objectives of this project are:

1. To demonstrate practical thermodynamic temperature realisation and dissemination from 4 K to 25 K with targeted measurement uncertainties of 0.3 mK ($k=1$) using at least three independent thermodynamic methods (Dielectric Constant Gas Thermometry - DCGT, Refractive Index Gas

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union’s Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: July 2024

Thermometry - RIGT and Acoustic Gas Thermometry AGT) to, at least, two NMIs without primary thermometry capabilities in this range, using practical temperature sensors (e.g. capsule-type RhFe or Pt thermometers) as transfer standards.

2. To demonstrate practical thermodynamic temperature traceability in the range 25 K to 300 K using at least two independent thermodynamic methods (Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) to, at least, two NMIs without primary thermometry capabilities in this range, using practical temperature sensors (capsule-type platinum resistance thermometers) as transfer standards. Target uncertainty 0.25 mK at 25 K and 0.6 mK at 300 K ($k=1$).
3. To develop a coherent framework for thermodynamic temperature dissemination to ensure consistency of dissemination of temperature from NMIs to users over the temperature range 4 K to 300 K whether it is by thermodynamic temperature or the defined scale (ITS-90) and develop a recommendation to CCT about the measurement uncertainties and the level of equivalence between these approaches to ensure that users have a clear understanding of the relationship between the two.
4. To establish a capability for the realisation and dissemination of thermodynamic temperature between 300 K and 700 K with $T-T_{90}$ target uncertainty of 0.6 mK at 300 K and 7 mK at 700 K ($k=1$).
5. To establish an integrated European temperature metrology infrastructure and facilitate the take up of the developed technology and measurement infrastructure by the measurement supply chain (accredited laboratories, instrument manufacturers), CIPM Consultative Committee for Thermometry (CCT), EURAMET and other RMO TC-Ts and relevant end users (industry and academia such as CERN, quantum computing, fundamental materials science communities, etc.).

Progress beyond the state of the art and results

Demonstrating dissemination of thermodynamic temperature from 4 K to 25 K (objective 1)

The current state of the art for temperature realisation and dissemination between 4 K and 25 K is through the defined scale (ITS-90). The situation is complex with different technical approaches and overlapping ranges; (0.65 K to 5 K $^3\text{He}/^4\text{He}$ vapour pressure thermometry, 3 K to ~24.6 K interpolating He gas thermometer and above ~13.8 K fixed points and capsule standard platinum resistance thermometer). Because of the complexity there are very few full ITS-90 realisations globally in this temperature range.

This project progresses the state of the art to demonstrate, for the first time, that low uncertainty thermodynamic methods may provide accurate temperature dissemination. Three thermodynamic approaches (Dielectric Constant Gas Thermometry - DCGT, Refractive Index Gas Thermometry – RIGT, and Acoustic Gas Thermometry AGT) will be used to perform the thermodynamic temperature calibrations of capsule-type thermometers to be used as transfer standards for dissemination to NMIs without primary thermometry capabilities. Target uncertainty 0.3 mK ($k=1$) in the range for the dissemination.

Initial work towards objective 1 is the characterisation, within a batch of resistance thermometers with different sensing elements by different manufacturers, of sensors which have the capability to reproduce and maintain a wire scale with uncertainties within a few tenths of a millikelvin. In the past, this function was performed by Rh-Fe thermometers from one single manufacturer but, these being no longer available, alternatives have to be found.

Within the M9 phase of this objective the following has been achieved: Capsule resistance thermometers of different kinds (Pt-Co, Rh-Fe and Pt) from different manufacturers were selected by six participants (PTB, INRIM, LNE, CNAM, NPL, TIPC-CAS), upon testing for their stability by repeated cycles between liquid N₂ and triple point of water temperatures. The selected capsules, collectively a set of 16 thermometers, were delivered to INTiBS, which is responsible for their initial ITS-90 calibration in the range 4 K to 25 K by comparison with a wire scale maintained other reference thermometers. ITS-90 calibration is underway and expected completed by early Autumn 2024, as scheduled. This work is preliminary to the distribution of the capsules to the NMIs responsible for thermodynamic calibration.

Demonstrating dissemination of thermodynamic temperature from 25 K to 300 K (objective 2)

The current state of the art for temperature realisation and dissemination in this temperature region is through calibration of platinum resistance thermometers to the defined scale (ITS-90).

This project advances the state of the art using two thermodynamic approaches (Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) to perform direct thermodynamic temperature calibrations without reference to ITS-90. Target uncertainty in temperature dissemination of 0.25 mK at 25 K and 0.6 mK at 300 K ($k=1$).

Within the M9 phase of this objective the following has been achieved: A total of 12 capsule-type standard platinum resistance thermometers (cSPRTs) have been selected and/or purchased by six project participants (INTiBS, CEM, INRIM, UL, CMI, SMD) responsible for their initial calibration over different sub-ranges of ITS-90 in the interval between the Triple point of neon (TPNe) at 25 K and the melting point of gallium (MPGa) at 303 K. Calibration activities are undergoing and expected to be complete by the end of 2024. Following ITS-90 calibration, the cSPRTS will be delivered to the laboratories responsible for their thermodynamic calibration.

Significant progress has also been achieved in the development of novel AGT apparatus by two NMIs (TUBITAK and CMI) who are developing thermodynamic calibration capabilities for the first time. TUBITAK has reported preliminary measurements of the speed of sound in argon.

Two external collaborators to the project will take part in the comparison of thermodynamic calibrations by delivering cSPRTs calibrated using AGT; these are the National Research Council of Canada (NRC), and the Korean NMI (KRISS). NRC has completed and is currently testing an AGT apparatus suitable for calibration between 25 K and the triple point of water (TPW). The AGT apparatus of KRISS will be used for calibration between 173 K and 303 K.

Development of a coherent framework for thermodynamic temperature dissemination (objective 3)

The current state of the art is that there is no coherent framework for disseminating thermodynamic temperature. The *mise en pratique* for the definition of the kelvin (*MeP-K*) states the allowable thermodynamic methods that can be used but does not address the many practical issues such traceable dissemination requires.

This project progresses the state of the art by developing a coherent framework that addresses these practical needs, by specifying the procedures for an inter-comparison of thermodynamic methods in order to prove their mutual consistency, ensuring the reliability of the dissemination of thermodynamic temperature to make it accessible in the future to the user community through a recommendation to the CCT.

Within the M9 phase of this objective the following has been achieved: Two protocols describing the procedures for the comparison and the dissemination of thermodynamic temperature, respectively in the ranges 4 K to 25 K and 25 K to 303 K, were initially drafted by CEM, repeatedly revised, and finally completed after being approved by all project participants. These documents detail the technical and organisational aspects involved in the comparison of thermodynamic calibrations, defining: timelines and modalities for the delivery, exchange and tests of the capsule-type thermometers used as transfer standards; communication protocols between the participants and the pilot (CEM) of the comparison; mixed delivery-ownership schemes to maintain the comparison rigorously blind; statistical and analytical methods to assess the consistency of the final results. The protocols also define the terms and the procedures for ITS-90 auxiliary calibrations which, combined with the results of thermodynamic calibrations, will provide a relevant number of ($T-T_{90}$) determinations as an additional important project outcome.

Establish capability for dissemination of thermodynamic temperature between 300 K and 700 K (objective 4)

The current state of the art is that only a few NMIs have made tentative steps towards developing capability for thermodynamic temperature measurements above 300 K.

This project progresses the state of the art by developing the capability to measure thermodynamic temperature to 700 K and develop values of $T-T_{90}$ with a target uncertainty of 7 mK at 700 K ($k=1$).

Within the M9 phase of this objective the following has been achieved: Dedicated technical discussion relating to high temperature AGT above 300 K has taken place during the project kick off meeting, followed by an online technical discussion between NIM, INRIM, NPL and an invited guest from NPL India in June. These informal knowledge exchange meetings will continue to be held approximately every 6 months for the duration of the project. An NPL scientist visited ITRI during May 2024 to commission the cylindrical resonator system. Validation tests were successfully performed at the maximum operational temperature of 300 °C, with encouraging results in preliminary speed of sound measurements in argon. Further tests and measurements are ongoing. NIM have performed microwave measurements from 335 K to 493 K, the results of which show

isotropic thermal expansion of the cylindrical resonator. The design of the high temperature AGT system of NIM has been completed, and a preliminary test from 473 K to 623 K has been performed. INRIM have designed and ordered a novel high temperature pressure vessel for their high temperature AGT system; delivery by the manufacturer is expected in late 2024.

Outcomes and impact

Key dissemination and communication activities

The project website has been established at www.direk-t.org under supervision and administration of UL. Major revision, update and add-ons of the website contents have been defined at M9 meeting to represent progress reported there and are currently being implemented.

Stakeholder community: The project stakeholder committee was established, and currently comprises 40 members with a wide spectrum of organisations including industry bodies, accreditation bodies, universities, regional metrology organisations and national measurement institutes outside Europe, as well as 5 companies that specialise in thermometry and temperature instrumentation and want to, in varying degrees, take benefit from early knowledge of the findings and outputs of the project. The first project newsletter is currently being completed to fully represent progress reported at the M9 meeting and will be circulated to the stakeholders in August 2024.

Communications activities towards scientific, end-users and industrial communities have started early in 2023, with several presentations of the project activities and objectives by the coordinator, the WP leaders and other project participants. These include invited oral presentations at workshops organised in concomitance with the EURAMET Technical Committee for Thermometry (TC-T) meeting in 2023 and at the Consultative Committee for Thermometry (CCT) Technical Workshop on “Traceability and Dissemination” within the 31st CCT meeting in 2024. In addition, poster presentations of the project were given at several congresses and conferences, spanning a range of different interests and audiences from application- to scientific-oriented, including the 26th Congress of Refrigeration (IIR 2023) and the 22nd Symposium on Thermophysical Properties.

Finally, preparative work has been started for the organisation of a summer school on “Contemporary issues in primary thermometry” addressed to metrologists from NMIs, calibration laboratories and researchers in scientific fields who require precision thermodynamic temperature measurements. As currently envisaged, the school may be held in late spring 2026 at the Universidad Internacional Menéndez Pelayo (UIMP) in Santander.

Outcomes for industrial and other user communities

Temperature is one of the most measured parameters in industry and by other users (e.g. climate change research). These developments will therefore have outcomes in almost all industrial sectors as well as more widely. However, most impact will be long-term (discussed below).

European accreditation bodies and calibration laboratories have a long-standing interest in the SI and its development. Links with such bodies have been established and the outcomes of this project with its implications for traceability will be fully communicated.

Temperature sensor manufacturers have signalled their interest in this project both directly and indirectly through trade bodies/learned societies. The outcomes of this project will be communicated to them through an e-newsletter and through the project website. Articles on the project outcomes will be published in trade body journals.

It is known that the introduction of ITS-90 caused significant indirect costs to industry through for example having to update standards, change algorithms and recalibrate reference standards. The consortium anticipates that dissemination of thermodynamic temperature will become widespread, negating the need for a new scale with industry avoiding significant costs.

Outcomes for the metrology and scientific communities

The project outcomes for the global thermometry community will be very significant, both through advances in the SI system of units (the kelvin) and contributions to the Consultative Committee of Thermometry.

For the global thermometry community. The realisation and dissemination of thermodynamic temperature, as opposed to defined scales, is a long-term objective. The project’s outcomes will mark a significant advance

towards that long-term objective by using multiple practical primary thermometry approaches to disseminate thermodynamic temperatures.

Specific outcomes will be:

- Capabilities for the dissemination of thermodynamic temperature demonstrated from 4 K to 25 K and from 25 K to ~300 K, with defined scale level uncertainties
- Thermodynamic temperature dissemination practicality demonstrated including the possibility to supersede the defined scale in these ranges
- A coherent framework for dissemination of thermodynamic temperature (4 K - 300 K) developed and recommended to the CCT
- The practicality of thermodynamic temperature dissemination at higher temperatures will have been investigated to ~700 K. The outcomes of DireK-T will also be incorporated into the Consultative Committee of Thermometry (CCT) advice and recommendations for use by the global thermometry community at the earliest opportunity. Possible outcomes are: revision of the *MeP-K*, revision of the CCT Strategy and revised consensus values of $T-T_{90}$.

Outcomes for relevant standards

This project will have a very significant outcomes for the whole thermometry community. This will be put into effect chiefly through the CCT, the global authority on temperature, and the relevant standards body for this work.

Key inputs into the CCT, influencing its guides and recommendations are:

1. Evaluation report on sensors for disseminating thermodynamic temperature from 4 K to 25 K
2. Practical demonstration of practical thermodynamic temperature dissemination from 4 K to 25 K
3. Practical demonstration of practical thermodynamic temperature dissemination from 25 K to 300 K
4. Recommendation report to CCT with framework for thermodynamic temperature dissemination to 300 K
5. New determinations of $T-T_{90}$ in the entire range 4 K to 303 K
6. New determinations of $T-T_{90}$ in the range 303 K to ~700 K
7. Report to CCT on approach to disseminating thermodynamic temperature >300 K

In addition, the key international stakeholders, chiefly the RMO TC-Ts, will be kept informed of the progress of DireK-T by annual written reports. There will also be an annual oral report to EURAMET TC-T.

Longer-term economic, social and environmental impacts

Thermometry is the most widely measured physical parameter so any change will have far reaching impact. This project will accelerate the paradigm shift in the practice of thermometry begun in the EMPIR JRP 18SIB02 Real-K project. There will be an increase in the use of primary thermometry, most appropriate for the needs of the user, to derive traceability to the redefined kelvin.

From an economic perspective. This change will first occur at the NMI level, but over time will be established in accredited laboratories. This will reduce the dependency on NMIs, providing traceability at reduced cost to the user. In the very long-term practical primary thermometry may be used to bring *in-situ* traceability at the point-of-measurement, through the deployment of thermometers with *in-built* traceability. Such innovations are necessary as fully autonomous production and reliable sensor networks are not possible without them.

From a social perspective. These developments may stimulate new industries/products/services, protecting high-value manufacturing employment. The kelvin definition has parallels with the metre redefinition. After the metre redefinition there was an expansion of optically based dimensional measurement approaches. Similar innovations could take place in thermometry with practical primary thermometry supplanting current approaches.

From an environmental perspective. As practical primary thermometry becomes a reality, *any* industrial process requiring reliable temperature measurement will, through the deployment of such sensors, always run

optimally, minimising energy use and harmful emissions whilst delivering a consistent quality product with zero waste. Reliable thermodynamic thermometry is essential to improve the reliability of global temperature monitoring and hence monitoring climate change. In addition, the issue of primary temperature measurement and thermometer calibration at liquid hydrogen temperatures will become highly relevant for the optimisation of processes and for custody transfer, once liquid hydrogen is introduced at large scale as part of a global hydrogen economy. Hydrogen is one of the technology pillars on which hopes to abate climate change rest.

Any user requiring long term reliable thermometry will benefit from *in-situ* practical primary thermometry having significant *social and environmental impact*. Practical primary *in-situ* thermometry will give nuclear power plant operators confidence of safe and efficient operation over the >30-year life. Long term nuclear waste repositories require reliable thermometry over decades.

In summary, because temperature is such a key parameter for industry and over many areas of human endeavour, it is anticipated there will be significant outcomes from this project. There will be stimulation of practical primary thermometry *per se* and the development of practical primary thermometry calibration facilities leading to significant new measurement capabilities for European NMIs and new products for European companies.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2023, 36 months
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Project website address: www.direk-t.org		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRIM, Italy 2. CEM, Spain 3. CMI, Czechia 4. CNAM, France 5. INTiBS, Poland 6. LNE, France 7. PTB, Germany 8. SMD, Belgium 9. TUBITAK, Türkiye 10. UL, Slovenia	-	-
Associated Partners:		
11. ITRI, Taiwan 12. NIM, China 13. NPL, United Kingdom 14. TIPC-CAS, China		

Publishable Summary 22IEM03 PriSpecTemp

Primary spectrometric thermometry for gases

Overview

Accurate air temperature measurements are critical for climate change monitoring and evidence-based policymaking for early mitigation/adaptation planning. Spectrometric thermometry overcomes several practical challenges posed by contact thermometry in air and industrial processes. However high uncertainties in molecular spectral parameters and adoption to elevated temperatures hinders its use. The project will integrate knowledge and infrastructure across the EU to improve, standardise and implement novel, non-contact methods including primary ro-vibrational spectroscopic thermometry. This will be cross-validated against other non-contact and the ITS-90 standard methods. Ultimately, a new hybrid calibration service with minimal long-term drift will support SI-traceable calibration of classical contact thermometers in gas and air.

Need

The effect of climate change is paramount, exemplified by record drought and flooding on several continents. The latest IPCC report suggests that the EU is the most affected region in the World with almost doubled warming effects. Mitigation and adaption plans have received increased priority on WMO's agenda and by ministers and policymakers. Therefore, informed decision making tailored by clear uncertainty assessment is essential not only for optimising resources but also to understand climate change predictions better. Accurate gas/air temperature measurements are crucial for underpinning these issues.

The limitations of contact thermometers for gas/air measurements are investigated in the EURAMET project Air Temperature Metrology. Low heat transfer of gas/air leads to amplification of self-heating and radiation effects, causing biases up to 200 mK. Spectrometric methods directly measure the thermodynamic temperature of molecules/gases and have been advanced in recent years with respect to both methodology and optical technology, demonstrating accuracy at a few tens of mK level. Currently, the method is mainly limited by the accuracy of spectral line intensities of probing gases (e.g., CO, CO₂, O₂), the lack of SI-traceability and validations against existing primary standards and ITS-90.

Furthermore, gas/air temperature is a critical parameter in many international ISO/DIN/CEN standards and a strategic target quantity of the CIPM CCT committee. It is also needed to optimise industrial production processes where contact thermometry suffers from well-known limitations in real conditions. Knowledge of accurate temperature at 10 mK and below is vital for fundamental metrology fields e.g. pressure and length.

Combining the state-of-the-art *ab initio* calculations, broadband ro-vibrational spectroscopy and recent advances in optical techniques forms a strong basis for an accurate primary gas/air temperature method to provide high accuracy calibration of contact thermometers.

Objectives

The overall objective of the project is to define and develop a new primary traceable spectroscopic gas temperature measurement approach over a temperature range of 200 – 400 K with a target uncertainty of 10 mK.

The specific objectives of the project are:

Report Status:
PU – Public, fully open

Publishable Summary

Issued: June 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



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1. To perform high accuracy quantum mechanical calculations on essential line parameters (line intensities and their rotational and vibrational dependence) of selected ro-vibrational bands of candidate “sensor” molecules (e.g., CO, CO₂, O₂) for temperatures in the range of 200 K to 400 K.
2. To perform high accuracy measurements of optimal selected molecular transitions (e.g., CO, CO₂, O₂) using high-resolution Fourier-transform spectroscopy (FTS) infrastructure, comb-assisted cavity ring-down spectroscopy (CA-CRDS) such as Doppler Broadening Thermometry (DBT), Cavity Mode Dispersion Spectroscopy (CMDS) and comb-based broadband techniques. To retrieve essential line parameters with high accuracy using refined line shape models (e.g. IUPAC recommended Hartmann-Tran profile). To compare and validate the *ab initio* results from objective 1 using the best experimental values.
3. To develop the methodology of multi-line ro-vibrational spectrometric gas thermometry (RVSGT) and to evaluate its performance under metrologically controlled laboratory conditions in the range of 200 K to 400 K, adopting spectral parameters from objectives 1 and 2. To develop the infrastructure for primary gas temperature measurements by updating existing NMI FTS infrastructure with a target uncertainty of 25 mK, to correspond to 0.1 % accuracy in relative line intensities of the probed molecular absorption lines.
4. To cross-validate spectrometric gas thermometry from objective 3 against other methods for the determination of thermodynamic temperatures (e.g., DBT, refractive index gas thermometry (RIGT), or via ITS-90 referenced SPRTs and T-T₉₀) maintained at NMIs. To adapt the NMIs’ optimum experimental capacities and proven test scenarios to identify further opportunities to improve the uncertainty to 10 mK.
5. To demonstrate the establishment of an integrated European metrology infrastructure for primary spectrometric thermometry for gases and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, European and international technical committees on thermometry (CCT, EURAMET and other RMOs TCs) and end users (remote sensing, automobile industry and aerospace industry).

Progress beyond the state of the art and results

Objective 1: Development of the primary RVSGT with targeted accuracy of 25 mK (k = 1)

Critical evaluation of the methodologies used for broadband spectroscopic thermometry will be made, identifying advantages of each method, and providing full GUM uncertainty estimations. HT line shape models will be adapted to take full advantage of the high SNR ($>10^5$) obtained, to meet the uncertainty target of 25 mK.

The planned calculation on the O₂ A-band has been completed. A manuscript to be submitted to a peer review journal.

A sensitivity study of quantum mechanical calculations toward direct characterisation of the uncertainty of *ab initio* calculations, using the CO molecule as the benchmark system has been performed.

Objective 2: Accurate spectral line intensities of CO and CO₂ with 0.1 % uncertainty

Calculations of CO and CO₂ absolute and relative line intensities with accuracies better than 0.1 % and 0.03 %, respectively, will be performed; these go beyond the state-of-the-art accuracy of 0.5 %. This will be achieved by implementing a multi-reference method (MRCI-SD), which includes high order corrections.

Line intensities of CO and CO₂ spectra will be measured in multiple temperature steps with accuracies better than 0.1 % using complementary techniques: FTS, CRDS, CMDS and TDLAS. Spectral line parameters will be retrieved using IUPAC-recommended HT profiles and cross validated among the techniques and with *ab initio* calculations. The potential of the cutting-edge CMDS technique, demonstrated for the CO molecule, will be applied to CO₂.

The line intensities of ten selected lines of the CO 3-0 band in the 1.57 μm spectral region have been measured and evaluated using different techniques including cavity mode dispersion spectroscopy (CMDS), Fourier-transform Spectroscopy (FTS) and cavity ring-down spectroscopy (CRDS). The standard uncertainties of the measured line intensities range from 0.08 % to 0.11 %.

An article titled Reference-free dual-comb spectroscopy with inbuilt coherence, has been published in the prestigious journal Optics Letters 49, 2473-2476 (2024). This work significantly simplified the experiments using dual comb spectroscopy without sacrificing the measurement precision. This is a step towards practical and accurate gas thermometry using dual-comb spectrometers.

The absorption spectra of pure oxygen and its mixtures with nitrogen in the 760 nm spectral region (also known as the A-band) using a high-resolution Fourier-transform spectrometer (FTS) in the pressure range between 450 hPa to 1100 hPa. Extensive uncertainty evaluation for every wavenumber in every spectrum was performed.

Comparison between several laboratories (CCQM-P229 pilot study) of the line intensity of the CO 1.57 μm band led to the most accurate reference line intensities and sub-permille agreement between mean experimental and ab initio data.

Objective 3: Improved accuracy of ambient air spectrometric thermometry based on improved O₂ spectroscopy

Studies of the oxygen (O₂) A-band will be performed to develop the oxygen spectroscopy-based air thermometer researched by VTT into an accurate and traceable technique for ambient air thermometry.

The first test of rovibrational thermometry at 296 K using the CO molecule and the CMDs technique has been performed. The difference between spectroscopic temperature and the ITS-90 reference value using primary SPRTs is only 20 mK with a standard uncertainty of 34 mK for the spectroscopic method.

The FTIR based rovibrational thermometry at 296 K has been tested using the CO₂ molecule. At 1 atm, the spectroscopic temperature agrees very well with ITS-90 calibrated PT100 sensors within uncertainty of 25 mK.

A new thermally stabilised optical cell for RVSGT has been designed. The thermal property is simulated using COMSOL software. A conference preceding article was submitted to the IMEKO Congress 2024 on the new design and the COMSOL simulations.

Objective 4: First primary hybrid (thermo-spectroscopic) calibration service bridging spectroscopic and contact thermometry

A facility for hybrid air temperature calibration of classical contact thermometer will be constructed and validated. This facility will allow the calibration of secondary thermometers directly against a RVSGT facility. This will provide an alternative calibration method compared with traditional methods, and give insight about the various influence parameters, potentially leading to lower uncertainties.

Outcomes and impact

To promote the uptake of the high-pressure calibration service, and to share insights generated throughout the project, results were shared broadly with scientific and industrial end-users. 1 paper was published in international journal "Optical Letters", 21 presentations and posters were made at international and national conferences and workshops. During the project, one international workshop was run on spectrometric gas thermometry with a section dedicated to remote sensing applications.

Outcomes for industrial and other user communities

The results from the project will have a wide impact on industry including food industry, steel industry, power plants, aerospace industry, pharmaceutical industry and biotechnology. In these sectors, gas/air temperature measurement is vital to improve production efficiency, reducing energy consumption and product quality control. In the food industry, temperature is regulated under European directives, such as 89/108/EEC, dealing with consumer well-being. In relation to the pharmaceutical industry, there are WHO recommendations regarding the temperature conditions in connection with transport and storage of medicines.

The project's hybrid facility for calibrating secondary thermometers against a primary thermometer will contribute to a reduction of the calibration uncertainty compared with traditional calibrations, thus having a strong impact on many users of secondary thermometers for air/gas temperature measurements.

Outcomes for the metrology and scientific communities

The project as well as its early results will be presented at the IMEKO Congress 2024, and the 1st CIPM-STG-CENV stakeholder workshop in Paris.

The consortium and project collaborators are developing the line lists of CO for the HITRAN database 2024 release. The HITRAN chair is being updated on this activity.

The consortium reached an agreement with the CCQM GAWG Task Group on Advance Spectroscopy to coordinate closely on the future international comparison on spectral line intensities, e.g. to choose common spectral bands and rotational lines for the CO₂ molecule for the CCQM international comparisons.

The consortium will frequently communicate with the new STG Task Team spectroscopy for the CIPM-STG-CENV on the project's results and outcomes.

The number of primary techniques for gas temperature measurement are currently very limited, the provided uncertainties are not optimal, and the involved economical and personal investments are huge. The project will provide a novel non-contact primary method in a broad temperature range of 200 K – 400 K with an uncertainty of 25 mK ($k=1$). Furthermore, this project aims to increase the understanding of the gas temperature concept and improve the quality of calibration procedures. Thus, the outcomes will be influential in all the related metrological and scientific communities including those with air temperature interests.

The multidisciplinary concept of the project will secure the impact on several scientific communities, including academia, research institutes and NMIs. Research outputs will be disseminated via trade journals, peer-reviewed papers, and international conferences.

The impact on NMIs ties in with the reduction of calibration uncertainties of thermometers used for air/gas temperature measurements. The new calibration facility will have significant impact on primary laboratories for other quantities, where the air temperature knowledge is vital for the understanding of the overall uncertainty of their services, e.g. mass and length calibrations.

The project will develop a new primary method for gas temperature measurements. This is extremely important since, the number of primary techniques for gas temperature are currently very limited, the uncertainties provided are not optimal, and the economical and personal investments involved are huge. Furthermore, the project will increase the understanding of the gas temperature concept and improve the quality of calibrations.

Outcomes for relevant standards

Due to the fundamental nature of this project, outcomes for ISO/EN standards is not expected within the first three years. However, on a longer time scale the outputs of this project will have strong repercussions in ISO/EN standards, because traceable air/gas temperature measurements, is a key quantity in many industry applications and in a lot of societal fields.

Several participants are members of the three most important technical committees for thermal metrology (CIPM CCT, EURAMET TC-T and IMEKO TC12) and chairman or member of relevant working groups of standardisation bodies (DIN, ISO, IEC). The participants will endeavour to ensure that the reference documentation or guidelines of these committees in the future incorporate the most relevant achievements. This includes joint presentations at the working group meetings and, where appropriate, written reports to the committees and working groups.

The participants in this consortium presented the project in the BIPM Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) Working Group on Gas Analysis (GAWG).

The EURAMET Project No. 1459 (Air Temperature Metrology) is a research project aiming to write EURAMET guidelines for calibration of thermometers in air. The project will provide beneficial input to these guidelines linking the results from the ATM to spectroscopic measurements.

The consortium is active in several technical expert teams of WMO/CIMO and will make sure that relevant outputs of this project are submitted to the most appropriate working groups of WMO/INCOM/SC-MINT for use as reference documentation and include them as WMO reference guides.

The consortium are active members of the European Metrology Network (EMN) for Climate and Ocean Observations, Energy Gases and Pollution monitoring and will keep these EMNs informed on respective EMN-relevant output from the project e.g., accurate spectral data for remote sensing, improved calibration of gas/air temperature sensors, and new possibilities for gas temperature measurement.

The consortium will present the project and its collaboration with CCQM-GAWG in the stakeholder workshop at the Annual General Meeting of EMN for Climate and Ocean Observations (EMN-COO).

Longer-term economic, social and environmental impacts

Air temperature measurements are the key quantity for determining the effect of Greenhouse gases on the climate. Accurate spectral line parameters for O₂ and CO₂, which considerably improve spectrometric thermometry in air, together with the development of a robust hybrid facility for contact thermometer calibration using spectroscopic techniques will directly affect the meteorology applied to detect climate change. For instance, the calibration services of the National Hydrological and Meteorological Agencies (NHMA) will considerably benefit from the new calibration facility.

The project will result in the improvement of multiple industrial processes due to improved gas temperature measurements. It will contribute to improved industrial competitiveness as a consequence of optimised production processes in industries such as automotive, pharmaceutical and aerospace. In addition, it will contribute to more efficient energy production through optimisation of temperature. The project will have a societal impact by providing information to support in addressing the rising temperature and the impact on environment and climate.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2023, 36 months
Coordinator: Gang Li, PTB Tel: 00495315923235 E-mail: gang.li@ptb.de Project website address: www.prispectemp.ptb.de		
Internal Beneficiaries: 1. PTB, Germany 2. CEM, Spain 3. DFM, Denmark 4. JV, Norway 5. TUBITAK, Türkiye 6. VTT, Finland	External Beneficiaries: 7. DLR, Germany 8. Iberoptics, Spain 9. RUG, Netherlands 10. SUN, Italy 11. UCM, Spain 12. UH, Finland 13. UMK, Poland	Unfunded Beneficiaries: n/a
Associated Partners: 14. UCL, United Kingdom		

Publishable Summary for 22IEM04 MQB-Pascal Metrology for quantum-based traceability of the pascal

Overview

Accurate pressure measurements are essential for key applications in climate, medicine, manufacturing, energy, science, safety and quality control. Previous projects demonstrated that quantum-based methods enable faster calibration of pressure sensors and lead to improved uncertainties. However, further work is needed to establish an integrated metrological infrastructure for a SI-traceable quantum-based pascal between 1 Pa to 1 MPa, as no primary standard currently exists that covers the whole range. This project will develop instruments and quantum-based methods and it will evaluate these in terms of practical applications to meet stakeholder needs. The project will aim at disseminating the technology to stakeholders with a minimal loss of performance, to allow for future products and services which are internationally competitive.

Need

Accurate, reliable, and cost-efficient pressure measurements are key for a variety of applications within a broad spectrum of industrial, scientific and regulatory sectors. Examples are altitude determinations to prevent airplane collisions as well as frequent unnecessary flight manoeuvres, the operational safety of power plants, leak prevention in the storage of toxic or nuclear waste, and the assurance of medical sterility. The importance of these measurements was expressed by the Comité international des poids et mesures (CIPM) in the 2017-2027 strategic document of the Consultative Committee for Mass and related quantities (CCM), and by the EURAMET Technical Committees for Mass and related quantities (TC-M) in their guidelines (roadmap).

While current methods rely on realising the pascal, the unit for pressure, through conventional means such as force over area, the revision of the SI-system in May 2019 opened an alternative path to realise the pascal by measuring the refractivity and the temperature of a gas. Such a realisation of the pascal, and other similar quantum-based approaches, do not depend on weights or movable parts, but instead measure the gas properties directly, using density-based methods. This will decrease uncertainties and at the same time will improve the efficiency of calibration chains. While significant efforts within Europe and internationally have proven that quantum-based methods have the capability to supersede conventional methods in certain relevant pressure ranges, there is not yet any realisation that has successfully combined all the advantages of the techniques.

To make full use of the inherent potential of these methods, it is crucial to consolidate and integrate expertise and efforts in Europe, so that quantum-based high-performance instrumentation (i.e. based on Fabry-Perot (FP) refractometry) can be realised, and consequently utilised. This includes improved uncertainties with a pressure-independent term of 2 mPa and a pressure dependent term of 10 ppm ($k=2$) for the realisation of the Pascal in the 1 Pa to 30 kPa range. Without the existence of standards that can provide these low uncertainties for this pressure range, several independent realisations are needed for comparison and validation purposes. In addition to primary realisations, the density-based methods offer advantages of ease of use, time savings, potential cost savings, compactness, and robustness, making them an excellent choice as pressure sensors or transfer standards. Based on practical experience and the plans of industrial stakeholders, the 1 Pa to 1 MPa range must be covered soon, and this pressure range must be targeted with an expanded uncertainty of 5 mPa + 30 ppm. To ensure acceptance of the novel methods amongst metrology and industry, an inexpensive, safe, and well characterised measuring gas with a high measuring effect is required. Nitrogen is an ideal candidate, and it is already widely used for conventional pressure measurement. Despite its broad use, there is a surprising lack of knowledge particularly for the dielectric and optical properties, and more work is required on this for a broad temperature and frequency range. This way, nitrogen and the corresponding

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European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: April 2024

infrastructure can be maintained conveniently which is expected to increase the acceptance of the novel methods. However, to promote acceptance of this, all results must be validated, which can be done through ring-type comparisons as well as comparisons with the best available standards. Furthermore, an investigation of the long-term stability is needed to show the extent to which the new quantum-based methods potentially do not require recalibrations.

Objectives

The overall objective of the project is to establish a metrological infrastructure for a traceable quantum-based pascal in the 1 Pa to 1 MPa range via the realisation of instrumentation and dissemination of the technology with minimal loss of performance to stakeholders. The methods will also be evaluated in terms of practical applications.

The specific objectives of the project are:

1. To develop high-accuracy primary pressure instruments based on Fabry-Perot (FP) refractometry for traceability to the pascal and covering the 1 Pa to 30 kPa range. The target uncertainty is 2 mPa + 10 ppm ($k=2$).
2. To develop validated quantum-based methods (including FP-based techniques, Rayleigh scattering, and polarising gas thermometry methods) to enable traceability within the 1 Pa to 1 MPa range with a target uncertainty of 5 mPa + 30 ppm ($k=2$). Applications should include gauge mode measurement, measurement of dynamic pressure and measurements with nitrogen and dry air. The concepts of miniaturisation and transportability should also be investigated.
3. To improve the metrological reference data and estimate the relevant uncertainties for the thermodynamic and electrodynamic properties of primarily nitrogen, i.e., density and dielectric virial coefficients, temperature dependent static and dynamic polarisabilities. The target uncertainty of the molar polarisability is less than 10 ppm.
4. To verify that the developed instruments utilising the developed quantum-based methods are consistent with their combined uncertainties and with existing primary standards, as well as to assess their long-term stability.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (EMN Quantum, European initiatives like the quantum flagship), standards developing organisations (CCM WGPV, EURAMET TC-M, ISO TC112) and end users (key stakeholders from science and industry).

Progress beyond the state of the art and results

By developing quantum-based methods for pressure measurement, this project aims to establish not only one, but at least three, fully operational quantum-based primary FP-refractometers. The project will also investigate, and improve upon, quantum-methods in general and investigate their possibility for a multitude of applications e.g. for the measurement of dynamic pressure and gauge mode measurements. Furthermore, theoretical calculations of the relevant properties of nitrogen, as well as verification and comparison against conventional methods, will be carried out. This project builds on the results and conclusion from its predecessor, EMPIR project 18SIB04 QuantumPascal, which successfully demonstrated the potential of quantum-based methods.

Realisation of primary FP-refractometers (Objective 1)

This project aims to improve the performance of FP-cavity-based refractometers, by consolidating efforts and recent progress across Europe. The goal is to demonstrate a confirmed uncertainty of at least 2 mPa + 10 ppm ($k=2$) in the 1 Pa to 30 kPa range. As part of this close collaboration, a further factor influencing the result of the pressure measurement using refractometry has already been uncovered. This is the influence of the laser power. Although this is very small, it depends on the pressure, gas type and design and must be considered to achieve the desired uncertainties. A simple but sufficiently accurate model was developed and confirmed several times experimentally, which quantifies this influence and thus allows the correction of discrepancies in the measured pressures using helium and argon. Furthermore, in an integrated effort, where the participants

will collaborate closely, at least three instruments in at least three different countries will be realised. This will effectively establish an infrastructure consisting of several primary FP-based refractometers across Europe. This will be a significant step beyond the current state-of-the-art, given that currently only two fully characterised systems exist in Europe.

Development of quantum-based methods for traceability and practical applications (Objective 2)

To fully utilise the advantage of quantum-based methods beyond their use as potential primary standards, efforts will be put into further investigation and improvement of systems based on Rayleigh scattering, polarised gas thermometry, and non-primary FP-based refractometers. These methods will be developed to jointly provide traceability in the range from 1 Pa to 1 MPa with a target uncertainty of 5 mPa + 30 ppm ($k=2$). Furthermore, to bring the technology within reach of stakeholders and industry, these novel methods will be developed and investigated to address important practical applications, such as the measurement of atmospheric pressure (gauge mode), the measurement of gas with unknown refractivity, and dynamic measurements, and the feasibility of realising transportable and miniaturised devices.

In addition to the efforts for primary FP refractometry, one of the system designs was changed in such a way that the maximum addressable pressure range could be increased to at least 300 kPa. With respect to the non-FP-based techniques, two Rayleigh scattering-based systems are currently under development. One is a newly set up to allow for dynamic measurements using a frame rate faster than 1600 fps, and the other one is updated to improve its temperature stability (to be within 5 mK), extend the maximum working pressure (up to 2 MPa), and further optimise the optical layout. The influence of the thermomolecular effect on a cryogenic polarising gas thermometer was further characterised. As a preliminary investigation, a gold-plated, stainless steel triaxial ellipsoid, modified with a thick copper disk to form two electromagnetically separated but thermally coupled hemi-ellipsoidal cavities, has been used for RIGT (Refractive Index Gas Thermometry) at constant temperature (273.16 K), but this configuration was not accurate enough to reach the target uncertainties, due to non-negligible drifts. Instead, a single copper cavity was prepared and is now under characterisation using helium gas to assess the pressure-induced deformation and calculate the compressibility coefficient.

Metrological reference data for nitrogen (Objective 3)

While the relevant properties of helium can be calculated with an uncertainty of less than 1 ppm, which was addressed within EMPIR project 18SIB04 QuantumPascal, nitrogen is by far the most used gas by national metrology institutes (NMIs), calibration laboratories and industry. Furthermore, since its refractivity is eight times higher, and it is much easier to work with, it offers significant advantages over helium. Despite this, there is a surprising lack particularly of accurate dielectric data for nitrogen. Due to its more complex structure, a combination of highest-level experiments and theoretical *ab-initio* calculations is used in this project to determine the required values. By providing a complete and validated set of all of the required properties for nitrogen beyond the state-of-the-art, this project aims to enable the use of nitrogen for the targeted quantum-based methods.

First results include the magnetisability, which has a small but not negligible contribution in the order of 10 ppm to the refractivity was calculated with an estimated relative uncertainty of 1 %. The values are publicly available on the platform Zenodo (<https://zenodo.org/communities/mqb-pascal/>). Also, recalculations of the second density virial coefficient utilising an updated empirically fine-tuned two-body potential were performed with two different methods (semiclassical and path integral Monte Carlo) and yielded consistent results in the investigated temperature range from 50 K up to 3000 K. To calculate the polarisability and the corresponding dispersion, the bond length of the nitrogen molecule is required first. These preparatory calculations were performed, including the Lamb shift of the vibrational energy levels, and published in Phys. Rev. A ("Atomic Bethe logarithm in the mean-field approximation").

Comparisons and stability assessments (Objective 4)

This project will carry out several comparisons between quantum-based methods and conventional transfer standards aimed at providing reliable data to assess the performance and stability of quantum-based systems, and therefore pave the way to the widespread use of these methods and systems. The quantum-based instrumentation will also be subject to an extensive circular comparison, which will be carried out with highly stable conventional standards. By utilising the stability of conventional standards, the goal is to be able to show that the newly developed instruments agree within their claimed uncertainties.

Work towards this objective has not yet started.

Outcomes and Impact

The project has a growing stakeholder community. In addition to various activities at conferences, such as presentations and posters, stakeholder workshops are planned to take place in the future, where the information will be presented in a compact format and there will also be an opportunity to engage with stakeholders. Datasets uploaded to the Zenodo repository can be found here: <https://zenodo.org/communities/mqb-pascal/>.

Outcomes for industrial and other user communities

The primary outcome of the project is to develop quantum-based pressure standards i.e. systems and methods. As the methods offer potential for improved calibrations in terms of performance, speed and cost, the outcomes of the project are expected to be taken up by a wide range of stakeholders that rely on accurate and precise pressure measurement, such as pressure sensor manufacturers. This project also aims to address relevant practical applications, such as measurements of air, measurements in gauge mode, and dynamic measurements (of non-constant pressures). It is expected that this will have a significant impact for industrial end-users.

To foster the uptake of the results, considerable engagement with a multitude of stakeholders will take place throughout the project. The training and hands-on demonstration of the novel methods which are planned within the project aim at promoting early uptake of the technology by stakeholders and end-users e.g. sensor and instrumentation manufacturers, to allow for future competitive products and services.

Outcomes for the metrology and scientific communities

The metrological and scientific communities will be the first to benefit from this project, which will integrate capacity and efforts within Europe to establish an infrastructure of quantum-based methods and realise at least three fully operational FP-based refractometers in at least three different countries. As these instruments have a target uncertainty of $2 \text{ mPa} + 10 \text{ ppm}$ ($k=2$) in the 1 Pa to 30 kPa range, it will represent a significant improvement in the important realisation of primary pressure standards, particularly at pressures below the typical working range for piston-cylinder systems. To provide traceability up to the 1 MPa range, this establishment will be complemented by the continued development of other quantum-based systems.

The project's outputs will be disseminated to CIPM, CCM, EURAMET TC-M and the EMN-Quantum, as they are the prime repositories of developments related to pressure metrology and quantum-metrology. The active engagement of these key stakeholders will ensure that the outcome will be disseminated worldwide to NMI laboratories and subsequently to any user who needs improved, traceable measurements of pressure in order to increase their commercial capacity or to address specific upcoming scientific or societal challenges.

The improved quantum-based methods in general, have the potential to be taken up by several other scientific and metrology areas, such as density, temperature, length and time.

To promote the uptake of the results of this project by these communities, the consortium will invite them to attend the project workshops.

Outcomes for relevant standards

Currently, no documentary standards exist on this subject, due to the novelty of the quantum-based realisation of the pascal. To maximise the outcomes of the project, the consortium has liaised and will liaise closely with key metrological bodies, namely CCM Working Group on Pressure and Vacuum (CCM WGPV) and EURAMET TC-M Subcommittee Pressure to ensure that they are kept up to date. The developments and results obtained will be presented at the regular meetings and their feedback will be directly taken into account.

Furthermore, the consortium informed and will inform ISO TC 112 "Vacuum Technology" about the results achieved and will provide reports to this committee, so that they can use these and consider the inclusion of quantum-based methods in a future revision of existing standards (e.g. ISO 3567: 2011 and ISO 27893: 2011). Furthermore, this will initiate the preparatory process for the development of new standards.

Longer-term economic, social, and environmental impacts

A more accurate realisation of the pascal in certain pressure ranges will have impact on a wide range of communities. In addition to improved uncertainties, it indirectly affects quality and safety controls in a multitude of processes and applications. There are a number of companies in Europe that manufacture pressure gauges, vacuum pumps, and process tools, with their products being among the best quality in the world. More accurate

pressure standards will help the users to compare different instruments from different manufacturers and to select the most appropriate instrument for their application, which will have a positive economic impact for both manufacturers and end-users. The development of new technologies will also enable manufacturers to produce a completely new generation sensors that are more precise, less expensive and which can potentially self-calibrate. Therefore, the output of this project will lead to higher profit for European companies compared to their competitors.

Precise differential pressure assessments are important in many processes e.g., for climate control in critical environments. As an additional pressure difference of 1 Pa in a medium-sized cleanroom requires around 3000 kWh of additional energy per year, more accurate differential pressure measurements can lead to considerable energy-savings. The improved means to monitor operational conditions will contribute to safer and more efficient conditions at power plants and critical facilities that handle toxic substances. Furthermore, vacuum and pressure related processes are key to many industrial applications that require clean and well-controlled environments. Better control of vacuum and pressure processes will lead to both increased profit margins and to the reduction of chemical waste. Volume flow and gas composition (via partial pressures) can be determined more precisely, which is important for relevant quality control and billing. In medical applications, especially in early detection, even the smallest changes in the partial pressures of relevant marker molecules are of utmost importance. An example would be a non-invasive COVID test based on exhaled air at the airport.

List of Publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	10. FBK, Italy	16. Iberoptics, Spain
2. CEM, Spain	11. HSU, Germany	17. Toptica, Germany
3. CMI, Czechia	12. UCM, Spain	18. WIKA, Germany
4. CNAM, France	13. UM, Slovenia	
5. IMT, Slovenia	14. UmU, Sweden	
6. INRIM, Italy	15. UW, Poland	
7. LNE, France		
8. RISE, Sweden		
9. TUBITAK, Türkiye		
Associated Partners:		
19. INFICON LI, Liechtenstein		

Publishable Summary for 22IEM05 NEWSTAND

New calibration standards and methods for radiometry and photometry after phaseout of incandescent lamps

Overview

Accurate knowledge of the spectral irradiance of optical radiation produced by natural and artificial light sources is essential in many applications. Therefore, it is necessary to ensure the traceability of spectroradiometric measurements to the International System of Units (SI). For decades, the measurement instruments have been calibrated using transfer standards based on incandescent lamps. However, their availability is diminishing due to a production phaseout of incandescent lighting products. This project aims to provide adequate and affordable replacement transfer standard light sources and alternative procedures for the detector-based transfer of the spectral irradiance unit in the ultraviolet--visible--near infrared (UV-VIS-NIR) spectral range. It also aims to establish an integrated European metrology infrastructure around this key radiometric unit.

Need

Accurate knowledge of the spectral irradiance of the optical radiation emitted by artificial and natural light sources is essential in various fields of industrial (UV-curing, disinfection, photovoltaic equipment, general and horticultural lighting, etc.), environmental (solar radiation, essential climate variables, etc.), medical (sun beds, photobiological treatment, etc.) or scientific (analytical spectroscopy, plasma, etc.) applications. The range of applications requiring spectral irradiance measurements has grown dramatically in the last couple of decades due to the introduction of affordable new technology spectroradiometers, based on array detectors, and the introduction of digital capabilities for the *in situ* processing of the spectral data. The routine availability of data on the spectral characteristics of optical radiation sources is seen as one of the technological enablers for producing higher-quality products, information and services.

Traceable spectral measurements of optical radiation are also required for the enforcement of many European regulations, directives and standards aimed at protecting the population against deleterious factors and sustainable energy use (DIRECTIVE 2006/25/EC, "on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)", Commission Regulation (EU) 2019/2020 "EcoDesign for light sources and separate control gears", EN 12464-1 "Light and lighting — Lighting of work places — Part 1: Indoor work places", EN 14255-1 to EN 14255-4 "Measurement and assessment of personal exposures to incoherent optical radiation", and EN 60335-2-27 "Household and similar electrical appliances - Safety - Part 2-27").

Incandescent lamp-based transfer standards have been used for decades for the calibration of spectroradiometers. Certain selected types of quartz-tungsten-halogen (QTH) lamps have been applied to disseminate the spectral irradiance unit in the spectral range from 250 nm to 2500 nm. However, the market availability of such lamps, and their applicability for this metrological purpose, is diminishing due to their production being phased out following the ban on incandescent lighting by the European Commission in 2009 [DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009, "Establishing a framework for the setting of ecodesign requirements for energy-related products," OJ L285, 10–35 (2009)] and by a technology change to solid-state-lighting (SSL) products. Therefore, there is an urgent need to develop alternative transfer standards using new-technology light sources, preferably with smooth

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

spectra over the entire UV-VIS-NIR spectral range (objective 1). Detector-based dissemination methods are also urgently needed as an alternative to source-based methods (objective 2). The need for new standards and traceability methods, triggered by the transition to solid-state lighting, has been expressed in research strategy papers by the European Association of National Metrology Institutes (EURAMET) [EURAMET Strategic Research Agenda for Metrology in Europe, V1.0 (03/2016), <https://www.euramet.org/publicationsmediacentre/documents/>], by the International Commission on Illumination (CIE) [CIE Research Strategy 4: New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry, <https://bit.ly/34gDee3>], and by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM) [CCPR Strategy Document 20222032, available at <https://www.bipm.org/en/committees/cc/ccpr>]. The new source-based transfer standards and detector-based methods developed require sound metrological validation through intercomparisons at all levels of the metrological traceability pyramid in order to demonstrate their metrological applicability for dissemination of the spectral irradiance unit with transfer uncertainties as low as 1 % ($k = 2$) (objective 3). Good practice guides for using the new-technology transfer standard sources and calibration procedures (objective 4) are needed to facilitate their adoption by the end user communities from the measurement supply chain (calibration and testing laboratories), standards developing organisations (CIE Division 2), technical committees (EURAMET TC PR, CCPR) and end users (manufacturers and users of spectroradiometers) and to establish an integrated European metrology infrastructure (objective 5).

Objectives

The overall objective of this project is to assure the SI-traceable measurement of spectral irradiance from natural and artificial sources of optical radiation and to develop the metrological infrastructure required for these measurements. This is necessary because the incandescent lamps, which are currently used as transfer standards, are being phased out. The specific objectives of the project are:

1. To develop new transfer standard sources for spectral irradiance in the ultraviolet-visible-near infrared (UVVISNIR) spectral ranges, built on new-technology products, such as narrowband and broadband LED sources, radiant dye-coated integrating spheres, laser-driven plasma light sources (LDLS) and white-light broadband lasers, to replace current transfer standards that are based on incandescent lamps. The specific requirements for the spectral irradiance of the new standard sources are: i) well-defined and fit-for-purpose spectral and geometric properties, ii) long-term stability, iii) reproducibility, iv) robustness, and v) compatibility with existing calibration facilities. As a new approach to creating transfer standard light sources, wavelength-tuneable narrowband light sources, with a sub-nanometre spectral bandwidth will be built as well. The new standard sources should allow dissemination of the spectral irradiance unit with transfer uncertainties as low as 0.5 % ($k = 2$).
2. To develop novel methods to enable the detector-based traceability of spectral irradiance measurements as an alternative to the incandescent lamp-based dissemination of the unit. This will involve i) the definition of the minimum requirements for the relevant properties of (array) spectroradiometers to be suitable as transfer standards and the selection of the instruments for the work within the project, ii) comprehensive characterisation of the selected instruments for all relevant properties and their calibration with respect to the spectral irradiance responsivity, iii) development of a versatile digital twin model of a transfer standard spectroradiometer that will enable the transfer of the instruments' characterisation and calibration results to the end users' applications and it will also enable the associated measurement uncertainties to be determined under changing measurement conditions, and iv) elaborating and documenting the concept needed for the transfer of the calibration results from one spectroradiometer instrument to another.
3. To demonstrate the metrological applicability of the new standard sources and methods, developed in objectives 1 and 2, in spectroradiometric applications involving spectral irradiance measurements in at least 3 end user sites with total uncertainties as low as 1 % ($k = 2$). This will be performed via interlaboratory comparisons and a measurement comparison campaign involving end user applications (i.e. solar radiation measurements, actinic radiometry, photovoltaics, lighting, and colour).
4. To develop good practice guides for the use of the newly developed transfer standard light sources, for the selection of spectroradiometers as transfer standard instruments and the respective calibration procedures, and for the use of the digital twin of the calibrated array spectroradiometers. These good

practice guides will enable the measurement methods and devices developed by the project to be implemented.

5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration and testing laboratories), standards developing organisations (CIE Division 2), technical committees (EURAMET TC-PR, CCPR) and end users (manufacturers and users of spectroradiometers).

Progress beyond the state of the art and results

Developing new standard sources for spectral irradiance

Current state-of-the-art transfer standards for spectral irradiance, in the spectral range from 250 nm to 2500 nm, are either based on 1000 W quartz-tungsten-halogen lamps or on other lower-power and lower-quality lamps.

This project will develop transfer standards for spectral irradiance using new-technology light sources and other approaches for calibrating spectroradiometers in the UVVISNIR spectral range. This will enable dissemination of the spectral irradiance unit with transfer uncertainties as low as 0.5 % ($k = 2$). The new-technology-based sources and components chosen for the development of the new transfer standards include narrow and broadband LEDs, enabling coverage of the spectral range from 270 nm up to 1700 nm, radiant dyes with an emission spectrum in the spectral range from 900 nm to 1700 nm and laser-driven light sources operating in the spectral range from 200 nm up to 2500 nm. Moreover, a narrowband spectrally tuneable light source will be developed as a transfer standard for the calibration of spectroradiometers throughout the spectral range from 280 nm to 1650 nm, covering most of the needs of the solar measurement community.

Developing novel methods to enable the detector-based traceability of spectral irradiance measurements

Common traceability chains for spectral irradiance measurements are built on light sources, which are used to transfer a spectral irradiance calibration from the primary standards to end user applications.

This project aims to establish an alternative approach that will use compact and portable array spectroradiometers as detector-based transfer standards. This concept is based on a novel method that will employ a digital twin of a transfer standard instrument. The digital twin combines the results from extensive characterisations and calibrations of the instrument with respect to all relevant instrumental properties contributing to its measurement uncertainties and a source code implementation of the model for the evaluation of the spectroradiometer data. This digital model will enable the user to account for all of the instrument's characteristics during the measurements in their end user applications. This will depend on their respective boundary conditions, which differ from the boundary conditions in the calibration laboratory. To enable instrument-to-instrument transfer of the calibration, respective methods and quality assurance procedures will be developed. Finally, comprehensive user guides and software code will be developed and provided to the end user community in order to facilitate the uptake of the methods and the proper use of the transfer standard instruments.

Demonstrating the metrological applicability of the new standards and methods

This project will demonstrate the metrological applicability of both the newly developed transfer standard light sources, and the detector-based transfer standards, in different end user applications both at calibration laboratory level and in different end user applications. To achieve this, measurement comparison campaigns will be arranged with the goal of demonstrating spectral irradiance measurements with total transfer uncertainties as low as 1 % when using the newly developed transfer standards and methods. Measurement comparisons involving array spectroradiometers, as transfer standards for spectral irradiance, will be a first demonstration of, and a proof of principle for, the new methods. The measurement comparisons for the newly developed transfer standard sources and spectroradiometers are scheduled to start in 2025.

Developing good practice guides to enable the use of the new standard sources and methods

Currently guides and documented procedures are only available for using incandescent lamp-based transfer standards. This project will produce good practice guides that will be tailored to the end users of the newly developed transfer standards, which will be based on new-technology light sources and also for end users of the new dissemination methods, which will be based on transfer standard spectroradiometers. The good

practice guides will aim to support the implementation of the project's results in the integrated European metrology infrastructure. The development of the first good practice guide defining the minimum mandatory requirements for a spectroradiometer to be suitable for use as a transfer standard instrument and necessary characterisations and calibrations of the instrument was started within the first months of the project.

Outcomes and impact

To promote the project's goals and to interact with scientists and potential stakeholders, posters were presented at two international conferences, namely at NEWRAD 2023 in Teddington and at the CIE quadrennial session 2023 in Ljubljana. Furthermore, an oral presentation was given at the national symposium "XI. Ulusal Aydınlatma Sempozyumu" in Türkiye where mainly industry and business partners were present. A first stakeholder workshop was organised by the consortium and this was held virtually on 22 November 2023. The event attracted thirty stakeholders representing over twenty different organisations, including National Metrology Institutes, standardisation bodies, international metrology organisations, academia, test-and calibration laboratories, and companies specialising in lighting and optical measurement equipment. The project was further presented during the annual EURAMET TC-PR meeting in January 2024 and to the German standards development organisation DIN in March 2024. The project's website is being regularly updated and specific end-user communities are reached through posts on the online blog of the EMN Climate and Ocean Observation.

Outcomes for industrial and other user communities

This project will provide new calibration standards and procedures, together with the extensive good practice guides accompanying each of the project's outcomes, for the industrial and other end users that rely on spectral irradiance measurements in industrial, occupational health and safety, photovoltaic energy generation, efficient energy use, and climate and earth observation applications.

Industrial users that apply spectral irradiance measurements to control radiation-related technological processes, such as the curing of materials, or the disinfection of air, water and surfaces, will profit from the new transfer standards as they will enable measurements that are traceable to the spectral irradiance unit after the incandescent lamps, which are currently used as transfer standards, have been phased out. The new spectral irradiance calibration standards, procedures and calibration services will also promote the industrial development of new products (e.g. novel standard sources) around the new technologies.

End users, from occupational health and safety applications, will receive new spectral irradiance standards for use in the calibration of their spectroradiometers or radiometers. These are used for performing onsite spectral measurements and for the assessment of personal exposures to incoherent optical radiation at places of work, outdoors and in sunbeds.

This project will provide new standards and calibration methods, which are highly relevant for photovoltaic energy production. Spectral irradiance measurements are an essential part of the metrological support provided to the photovoltaic energy generation sector. The results of this project are also highly relevant to energy saving through the use of energy-efficient lighting. The production, planning and installation of energy saving lighting products is highly reliant on spectral information, for which the metrological dissemination of the spectral irradiance unit is mandatory.

The outcomes of this project will also be used by the earth observation communities. The applicability of the new transfer standards to calibrate the spectroradiometers, which are used for measuring terrestrial solar radiation, will be demonstrated during a measurement campaign. The participants will disseminate the outcomes of this project within the stakeholder community that is associated with the European Metrology Network on Climate and Ocean Observation.

Outcomes for the metrology and scientific communities

This project will deliver new transfer standards and dissemination methods to enable National Metrology Institutes (NMIs), Designated Institutes (DIs) and calibration laboratories to disseminate the unit of spectral irradiance to end users that are affected by the phaseout of standard incandescent lamps. The top-level metrological application of the transfer standards will enable the NMIs, DIs and calibration laboratories to compare their measurement capabilities at the International Bureau of Weights and Measures (BIPM) and the European Regional Metrology Organisation (RMO), i.e. from the EURAMET level down to bilateral interlaboratory comparisons. The new standard sources and procedures for the detector-based dissemination of the spectral irradiance unit, developed by the project, will meet the needs of a wide community of end users,

from metrology and other science disciplines, that measure the spectral properties of emitted radiation (analytical spectroscopy, plasma, luminescence, etc.).

The well documented implementation of a digital twin of the transfer standard instruments in an open-source code provided by the project will help the end users to benefit from the data yielded by instrument characterisations and calibrations. This will enable GUM-conforming propagation of the uncertainties and correlations into their measurement applications.

End user communities will be able to select spectroradiometers as transfer standard instruments using the project's user guide which defines the minimum mandatory specifications of an instrument. This guide will also help the NMIs and calibration laboratories to clarify the calibration needs of their customers.

Outcomes for relevant standards

This project will provide the metrological basis for many European Regulations, Directives and Standards that refer directly or indirectly to the spectral measurement of optical radiation. These are aimed at protecting the population against deleterious factors, sustainable energy use and the protection of the environment:

- DIRECTIVE 2006/25/EC, "on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)". This directive states that the risk assessment shall consider the level, wavelength range and duration of exposure to artificial sources of optical radiation.
- Commission Regulation (EU) 2019/2020 "EcoDesign for light sources and separate control gears". This regulation requires a minimal general colour rendering index (Ra). This quantity can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.
- EN 12464-1 "Light and lighting — Lighting of work places — Part 1: Indoor work places". This standard requires that authenticated general colour rendering index (Ra) and correlated colour temperatures (CCT) data shall be provided for the light source in the scheme by the manufacturer of the light source. The light sources shall be checked against the design specifications. These quantities can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.
- EN 14255-1 to EN 14255-4 "Measurement and assessment of personal exposures to incoherent optical radiation". These standards require onsite measurements in the spectral range from about 200 nm to 2000 nm. Some of the measurements, particularly in the UV, can only be performed using a spectroradiometer.
- EN 60335-2-27 "Household and similar electrical appliances - Safety - Part 2-27: Particular requirements for appliances for skin exposure to ultraviolet and infrared radiation". It requires that individual sunbed sessions shall have a maximum UV output that corresponds to the mid-day Mediterranean sun (UV index of 12) to avoid any risk of burns and to reduce the likelihood of accidents due to long exposure.

Longer-term economic, social and environmental impacts

The metrological traceability of spectral irradiance measurements in diverse industrial, health, scientific and environmental applications is currently based on incandescent lamps that are gradually vanishing from the market. After their complete phaseout, in the mid to long term, the dissemination of the spectral irradiance unit will be endangered. This project will provide new-technology transfer standards and methods to enable traceable measurements of spectral irradiance from artificial and natural light sources in the long term by the end user communities. Reliable and high accuracy spectral data from optical radiation sources, supported by the developments in this project, will be one of the technological enablers for high-quality products, information and services in different end user applications. The accurate assessment of terrestrial solar radiation, and the derived atmospheric parameters used as essential climatic variables, are mandatory for monitoring climate change and its effects on ecosystems, human health, agricultural production and food safety on a global scale.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2023, 36 months
Coordinator: Saulius Nevas, PTB Tel: +49 531 592 4115 E-mail: saulius.nevas@ptb.de Project website address: https://www.ptb.de/epm2022/newstand		
Internal Beneficiaries: 1. PTB, Germany 2. Aalto, Finland 3. CMI, Czechia 4. CNAM, France 5. CSIC, Spain 6. IPQ, Portugal 7. LNE, France 8. Metroserf, Estonia 9. RISE, Sweden 10. TUBITAK, Türkiye 11. VSL, Netherlands	External Beneficiaries: 12. ISFH, Germany	Unfunded Beneficiaries: 13. GGO, Germany 14. IS, Germany
Associated Partners: 15. METAS, Switzerland 16. NPL, United Kingdom 17. SFI DAVOS, Switzerland		

Publishable Summary for 22IEM06 S-CALe Up

Self-calibrating photodiodes for UV and exploitation of induced junction technology

Overview

Photonics and optics are exciting, rapidly evolving technologies of great value (over 100 billion € in EU) and of importance across industry, environment, health, medicine, energy, lighting and science. The photonic industry and standardisation organisations request miniaturised, cost-effective, integrated and self-calibrating measurement systems that cannot be provided by traditional methods. Recent developments exploiting predictable photodiodes in various ways have demonstrated improved uncertainty of responsivity to 10 ppm and the proof-of-concept of an NMI-on-a-chip suitable for miniaturisation. This project will demonstrate exploitation of the new photodiodes as built-in standards in various applications and develop improved standard detectors for the UV range by exploiting new methods.

Need

There is rapid and exciting technology development within photonics, which is one of six EU defined Key Enabling Technologies (KET) used in climate monitoring, medical treatment, health and photonic industries, energy saving illumination by light-emitting diodes (LEDs), electricity production, science, and many more applications. The technological development trend is towards miniaturisation, more integrated measurement systems and distribution of standalone sensor systems in possibly remote locations. Current metrological systems are not capable of calibrating photodiodes in integrated systems nor in remote locations. Therefore, the European technology platforms Photonics21 and Quantum Flagship highlight the integration of self-calibrating systems and products as one of the technology, research, and innovation challenges ahead.

Previous iMERA+, EMRP and EMPIR projects have developed the Predictable Quantum Efficient Detector (PQED), which has proven to have an extremely low external quantum deficiency (EQD) of around 10 ppm with an undetectable drift over 10 years. These properties make the PQED a very attractive calibration standard detector that complies well with the low-cost and high accuracy transfer standard requested by CIPM's Consultative Committee for Photometry and Radiometry (CCPR).

Demonstration of the utility and exploitability of the PQED's properties in various applications is necessary to increase their technological readiness level, bringing them closer to uptake by relevant industry and end-users.

The ultraviolet (UV) range is of great importance to health and earth observations but suffers from detectors with poor stability and lack of predictability. The International Commission on Illumination (CIE), as the world standardisation organisation for light and lighting, has requested research on new low-cost, high accuracy, primary standard detectors of optical radiation allowing better traceability from 200 nm – 2000 nm, which is of importance to industry and will also cover the UV range. Predictable UV detectors with improved stability will be developed in objective 3.

Improved understanding of the measurement system provided by advanced modelling of photodiodes will be explored in objective 1, supported by characterisation measurements from objective 4 will be key in enabling better traceability and will trigger new measurement techniques in remote and integrated measurement systems. In a similar way, dual-mode detectors are needed to enable a pure experimental self-calibrating measurement system in a wider range of applications, than those studied in objective 2 for future exploitation also outside the spectral range covered by silicon technology, where photodiodes cannot be accurately modelled.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: March 2024

Objectives

The overall objective is to demonstrate the use of improved PQED detectors and associated technology as an NMI-on-a-chip in various photonics applications and to develop models and improved detector manufacturing techniques in order to provide improved traceability into the more challenging UV and NIR spectral range.

The specific objectives of the project are:

1. To develop **3D simulation models** of photodiode charge carrier transportation in Predictable Quantum Efficient Detectors (PQED) for better physical representation, higher calculation speed, wider availability and improved uncertainty approaching 1 ppm between 500 nm and 900 nm, and to extend the quantum yield prediction from 400 nm down to 250 nm with an uncertainty better than 0.1 % and better than 0.2 % from 250 nm to 200 nm.
2. To **use PQEDs** with very low spectral responsivity uncertainty in the 400 nm to 850 nm range as built-in references **in different applications** (e.g. optical power measurement, fibre optics, pulsed laser radiation, photometry without $V(\lambda)$ filters) taking into account practical aspects, such as current measurements, stray light, geometry, heat and dark current variations.
3. To develop and **fabricate improved photodiodes for the UV range** and validate their stability and suitability as a spectral responsivity standard from 400 nm to 200 nm. Additionally, to develop thermal simulations and packaging technology of dual-mode detectors with heat equivalence better than 0.03 % suitable for implementation at any wavelength over the spectral range from 200 nm to 1000 nm.
4. To **extend the spectral response range** of photodiodes between i) 200 nm and 400 nm, and ii) 850 nm and 1050 nm, with a target uncertainty better than 0.2 %. For this, the improved detectors and packaging developed in objective 3, and improved charge carrier simulation and quantum yield modelling developed in objective 1, will be used.
5. To demonstrate the establishment of **an integrated European metrology infrastructure and to facilitate the take up of the technology** and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (CIE), technical committees (e.g. EURAMET TC-PR, CCPR) and end users (photonics industry).

Progress beyond the state of the art and results

Improved simulation models

The spectral responsivity of PQEDs are to first approximation given by fundamental constants and the radiation wavelength. Deviations from this ideal performance are given by internal quantum deficiency, reflectance and quantum yield models. In order to have a fully predictable standard detector all quantities have to be independently predicted.

The project builds on the EMPIR 18SIB10 chipS-CALe project, where improved self-induced PQED trap detectors with a record low external quantum deficiency below 10 ppm were developed for the 400 nm to 850 nm spectral range. Simplified 3D simulation models were developed and new experimental techniques where simulation fitting to experimental photocurrent measurement at only one wavelength was proven to be sufficient to predict the responsivity from 400 nm to 850 nm. In previous projects, quantum yield (QY) was found significant at wavelengths as high as 470 nm and to increase with decreasing wavelength. However, the quantum yield was also found calculable to an uncertainty around 200 ppm down to 360 nm. Current 3D simulation capabilities are limited to one NMI, on one type of software, with known limiting simplifications due to calculation speed and the current TRL-level in the 400 nm – 850 nm spectral range is around 3 to 4.

A new software package and two more partners are now involved in charge carrier simulation. Work is ongoing at three different sites to enable the simulation models to be run on high performance computer (HPC) systems to improve high accuracy simulation speed. The overall availability and simulation capacity is expected to improve significantly throughout the project.

In S-CALe Up simulation models will be used to

- I. improve predictability of the PQED to achieve an uncertainty that goes beyond the IQD losses,

- II. independently predict the spectral response of PQEDs from 300 nm to 1000 nm, the spectral range covered by the key comparison CCPR-K2.b.
- III. develop improved standard detectors and prediction methods designed for the UV spectral range from 200 nm to 400 nm, the spectral range covered by the key comparison CCPR-K2.c.

Furthermore, reflectance losses and quantum yield will be studied and modelled to enable the development of independently predictable standard detectors for the full spectral ranges covered by CCPR-K2.b (300 nm – 1000 nm) and CCPR-K2.c (200 nm – 400 nm).

Progress have been made on reflectance measurements covering the range of a predictable standard from 300 nm to 1000 nm. Reflectance is below the few ppm range from 400 nm throughout 1050 nm, but increases rapidly into the UV to 10 % down to 300 nm. The measured reflectance will be compared with other techniques as spectroscopic ellipsometry to extract the refractive indices and material thicknesses required to have a fully predictable standard. Initial measurements have been made and analysis of the data are in progress. Especially challenging are the long wavelength range where reflectance from the back surface interfere with the front surface reflection. However, this may be used to improve the predictability, confidence and robustness in the reflectance modelling and will be included in the analysis.

For the quantum yield (QY) progress in the measurement of relative spectral response down to 250 nm is published. The measured spectral response serves as a basis for calculating the QY and existing model describes the general background QY. However, more work is required to establish a model describing all features in the QY spectral dependence.

Applications for photometry, fibre optics and PICs exploiting PQEDs

The PQEDs have proven to be extremely stable with an undetectable drift, independent of wavelength, over ten years with a responsivity directly linked to fundamental constants. This makes the PQED an ideal transfer standard ready to be exploited in applications.

In S-CALe Up, three different applications for providing services to industry with the PQED as a built-in reference will be demonstrated, which will bring the technology closer to uptake by end-users. These demonstrators will simplify realisations, improve traceability and are expected to produce improved calibration and measurement capabilities (CMCs) with reduced uncertainty for the laboratories developing the demonstrators. For the filter-free photometers, partners have acquired PQEDs as a primary standard photometer and work is going on to reduce the uncertainty in the measurement. Spectral measurements of the source with improved calibration of wavelength scale has been conducted and spectral mismatch factor is estimated. Reflectance losses of the detector is also under study. The use of precision aperture and gas lensing effect from purging the PQED have been studied and concluded that purging should be done with synthetic air and not dry nitrogen.

A room temperature fibre optic PQED has been developed and exploited by mounting a fibre holder very close to the first surface of the PQED. Raytracing analysis with simulation software have shown that collecting radiation from two reflections are sufficient to achieve an uncertainty below 0.1 % with chipS-CALe developed PQEDs. It is therefore expected that collecting enough diverging radiation from a fibre tip, to gain high accuracy power measurements, should be easily achievable from standard single mode fibres.

Develop and fabricate improved photodiodes for the UV range and technology for improved photodiodes

Silicon transfer standard pn-photodiodes for the UV spectral range from 200 nm to 400 nm are known to deteriorate under UV exposure, but new process advancements have proven to produce more stable photodiodes. Alternative materials and diode types such as PtSi and GaAsP are also used, but they suffer from a large non-uniformity. The self-induced photodiodes in the PQED may be less susceptible to radiation damage, but this has not tested.

In this project, improved photodiodes for the UV range with improved and validated stability will be developed taking advantage of the predictability of the photodiodes. Combining simulation models and fast material characterisations will enable many different processes to be tested to produce optimum and robust passivation. In order to achieve required radiation hardness and still predictable photodiode, ultra shallow pn junctions is under development. Doping profiles as low as 25 nm with a peak concentration of $1E19\text{ cm}^{-3}$ is already achieved, which is excellent. The expected responsivity of detectors produced with the recipe will be estimated from lifetime measurements and 3D simulation models.

Furthermore, the influence and optimising of the current read-out contacts with carrier selective contacts will be studied. The idea behind the principle is to reduce the probability of recombination at the metal semiconductor interface. Two different processes for deposition is established and test samples are under development. Simulation models in Silvaco ATLAS is currently being adopted to design and optimise the carrier selective passivating contact structures.

In addition to developing new detectors, stability over the full spectral range for the intended use of chipS-CALe photodiodes from 300 nm to 1000 nm are under examination. Preliminary results so far show that the chipS-CALe photodiodes will degrade when exposed to high energy photons below 250 nm, but will maintain their stability when exposed to radiation down to 300 nm. Examining this preliminary conclusion will continue, but so far it is a very promising result.

Extended and validated spectral response scales and packaging technology for dual-mode

In this project, improved photodiodes and modelling will be exploited to establish and validate the fully predictable spectral response scales covering the CCPR-K2.c range from 200 nm to 400 nm and the CCPR-K2.b range from 300 nm to 1000 nm with a target uncertainty below 0.2 %. This will simplify the realisations of spectral response scale as fewer calibration points are needed, and will enable implementation of independent traceability techniques exploiting the state of the art PQEDs. Two different types of PQEDs are under development and in S-CALe Up new packaging enabling use of housing of regular Hamamatsu 1337-1010 is developed. 3-element trap detectors are assembled for testing and use in various measurements in the project. Standard 2-element trap detectors (PQEDs) are used and photocurrent vs voltage experiments have started with the aim of extracting the individual IQD with the use of 3D simulation models.

Improved packaging, for dual-mode experiment, suitable for future industrialisation and implementation with other types of photodiodes than silicon is under development. Alternative calibration methods based on purely experimental self-calibrating techniques referred to as dual-mode detectors (DMD) are promising and is generic methods to provide traceability to a wide spectral range. The techniques have been developed and demonstrated at room temperature with an uncertainty below 0.05 %. Current packaging technologies for dual-mode detectors are limited to silicon photodiodes, as they are heated through forward bias, and have a beam position dependent thermal non-equivalence around 280 ppm/mm. Improved experimental capability of dual-mode measurements have been achieved and an IQD of 0.00 +/- 0.04 % is achieved over +/- 1 mm around the central part of the detector with a radiant power of 366 μ W at room temperature. The uncertainty is limited by the beam position dependent thermal non-equivalence. New and more robust packaging is designed and assembled. Initial measurements have been made with promising results but highlighted also the need for refinement of the design.

Outcomes and Impact

The project had seven presentations of research outputs from the previous project and the S-CALe Up project at the NEWRAD2023 conference held at NPL September 2023, where PQEDs for the first time had its own session. 22 stakeholders from industry, academia and metrology community receive regular updates about the project progress through the publishable summary. Presentations at the Euramet TC-PR annual meeting and input to TC2-81 "Update of CIE 065:1985 (Absolute Radiometers)" have been made in a dedicated section on PQEDs. This document is a complete draft which is now ready for voting. New detectors, measurement and simulation services will be made available for the user community at the latter half of the project. Information about project progress will be found at the project website <https://scaleup.aalto.fi/>. The project has conducted a training course on request by a stakeholder in exploitation, wiring and measurements with PQEDs. A news article about PQED chips was published on Instagram.

Outcomes for industrial and other user communities

Industry in general require improved and simplified measurement standards suitable for miniaturisation. The development trend is moving in the direction of more compact and integrated systems, and this project aims to enable future implementation of traceability to such systems where existing measurement techniques are not capable of providing traceability. By exploiting PQEDs in specific metrological applications, cost efficient realisations of primary photometers and power meters of importance to industry will be demonstrated. The outstanding self-calibrating technology developed in the previous project 18SIB10 chipS-CALe is expected to continue to develop towards more user-friendly solutions so that more applications can profit from it. Implementation of PQEDs in applications will bring the technology closer to the market.

Outcomes for the metrology and scientific communities

Realising primary standard techniques based on silicon photodiodes outline new ways to provide traceability based on the built-in responsivity linked to fundamental constants. With the realisation of the units and their dissemination occurring through the same artefact, the PQED provides the means to shorten the traceability chain and improve the measurement uncertainty. The microelectronic processing makes the primary standard suitable for miniaturisation and integration into measurement systems where traceability was previously not achievable. Furthermore, the new techniques with predictable spectral response throughout the whole spectral range of interest will ensure better global harmonisation of measurement results and improved access throughout the metrological community to the highest metrological standards.

The structure in the project will enable NMIs to develop and exploit their specific niche of expertise which will be used to meet the project's overall goals, and to develop European robustness in services where more than one NMI can provide the needed services to stakeholders. This collaboration will strengthen the metrological expertise of all contributing NMIs, including small and emerging institutes, support EURAMET's goal for smart specialisation, and assure an internationally leading position.

Outcomes for relevant standards

The International Commission of Illumination (CIE) is the international standardisation organisation on all aspects of light and lighting. Today's conventional techniques for realising absolute standard detectors require expensive equipment, high skill levels to operate, time-consuming methods and interpolation functions to establish a continuous spectral response scale.

The early outcomes of this work will be shared with the following relevant CIE Division 2 Technical Committees:

- TC 2-81 Update of CIE 065:1985 (Absolute radiometers)
- TC 2-90 LED Reference Spectrum for Photometer Calibration
- TC 2-96 Revision of ISO/CIE 19476:2014 Characterization of the Performance of Illuminance Meters and Luminance Meters

The project will contribute to preparing updates to and replacements for CIE 250:2022 Spectroradiometric measurement of optical radiation sources and CIE 127:2007 Measurement of LEDs.

Many European regulations and standards refer directly or indirectly to spectrally resolved absolute measurements of optical radiation power, including European standard EN 14255 "Measurement and assessment of personal exposures to incoherent optical radiation" parts 1 to 4, and EN/IEC 62471:2008/CIE S 009:2002 - Photobiological safety of lamps and lamp systems". These standards require spectrally resolved measurements in the spectral range of about 200 nm to 2000 nm, both in the laboratory and onsite. Improved calibration uncertainty of spectrally resolved equipment will be available as a result of this project.

Longer-term economic, social and environmental impacts

The European photonics industry has grown from €76 billion in 2015 to €103 billion in 2019 with a growth rate of 7 % per year and a share of 16 % of the global market. Besides components and materials, the major application segments are photonics for consumers' IT, medicine and biology, environment, lighting and energy, and Industry 4.0, indicating its direct involvement in the challenges for the future. The largest segment in Europe, photonics systems for industry – was worth €19.2 billion in 2019 and accounted for a 40 % share in the global markets. Europe is well positioned in the field of photonics systems for production, i.e. industrial laser systems, semiconductor manufacturing and machine vision.

Photonics21 is one of the European Technology Platforms supporting the EU-defined KETs and has more than 3000 members from the photonic industry, research institutes, academia, and public service. Established contacts between the project consortium and Photonics21 will simplify the transfer of knowledge about project outputs to this important technology platform. Successful project outputs will meet Photonics21 WG5 strategic roadmap targets for the period 2021 to 2027, where they request "maintenance-free, self-calibrating sensors, high quantum efficiency" as both a technology challenge and a research and innovation challenge for optimised value; a need outlined also by Quantum Flagship. The microelectronics-based primary standard detector is suitable for miniaturisation and may be integrated with the evolving technology of Photonic Integrated Circuits (PICs) in the future.

The incoming and outgoing radiation measurements are key components of Earth Energy Imbalance (EEI). Using PQEDs as a reference in lab-based calibrations or in future spaceflights could improve future EEI measurements.

Healthcare systems are under increasing pressure due to the aging population. High accuracy radiometric measurements are needed for faster and less invasive techniques in medical diagnostic instruments. This ensures cost efficiency, for example, by enabling analyses of blood samples at the point of care and the fast return of results while the patient is present.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. JV, Norway	10. IFE, Norway	13. LMT, Germany
2. Aalto, Finland	11. SINTEF, Norway	
3. CMI, Czechia	12. USN, Norway	
4. CSIC, Spain		
5. INRIM, Italy		
6. Metroserf, Estonia		
7. PTB, Germany		
8. RISE, Sweden		
9. TUBITAK, Türkiye		
Associated Partners:		
14. SFI Davos, Switzerland		

Publishable Summary for 22IEM07 INFOTerm

Integrated European research, calibration and testing infrastructure for fibre-optic thermometry

Overview

The measurement and control of temperature plays a key role in achieving the goals of the European Green Deal for a low-carbon energy system. Fibre-optic thermometry is an emerging technology that can improve the measurement of temperature in extreme environments for energy providers and the industry sector due to distributed sensing and immunity to electromagnetic fields. However, fibre optic thermometers exhibit cross sensitivities to other quantities (e.g. strain, vibration, humidity) and ageing effects that need to be investigated, quantified and minimised to obtain traceable and reliable measurements. Therefore, this project aims to overcome the limitations that prevent the widespread use of fibre-optic thermometry by creating a dedicated European metrological infrastructure addressing research (e.g. measurement uncertainty), testing (e.g. industrial case studies), calibration (e.g. services and guides), and training (e.g. stakeholder workshop).

Need

Transforming Europe's energy system towards a higher share of renewable energy to meet the goals of the European Green Deal for a low-carbon energy system will require some infrastructure changes. For example, energy from wind and solar resources can be stored when production is high and released when less energy is produced. This can be achieved by thermal energy storage, such as tanks of molten salt at temperatures up to 560 °C, which require the measurement of the exact temperature and its distribution to quantify the loading state and to minimise losses through mixing. There is also a need to provide geothermal energy and seasonal storage of thermal energy in underground areas through multiple boreholes. Monitoring such boreholes can greatly improve system operation and integrity, but reliable temperature measurements with high spatial resolution are required along a path, not just at a few points.

Fluctuations in renewable energy production caused by local weather conditions increase the dynamics of the electrical grid and put additional stress on its components such as power cables and transformer stations. Monitoring temperature with instruments that are not affected by electromagnetic fields, such as fibre-optic thermometers, allows better utilisation of existing infrastructure. In addition, some high-temperature processes (e.g. silicon production for solar cells or semiconductors) require precise temperature monitoring and control for efficient operation and product quality. Conventional high temperature thermometers (mostly thermocouples) have serious limitations due to ageing and drift. Stable contact thermometers for temperatures up to 1600 °C are urgently needed.

Existing commercial fibre-optic systems are not traceable to the International System of Units (SI). Therefore, more work is needed to validate fibre-based thermometry and make its use in key industrial applications more attractive. Most fibre-optic thermometers have a Technology Readiness Level (TRL) between TRL4 and TRL7. However, for applications related to critical infrastructure monitoring and control, advanced manufacturing processes or quality control, this is not sufficient and independent verification, also known as TRL9, is required. TRL9 is provided by calibration services from accredited calibration laboratories, NMIs or an approved body under the Measuring Instruments Directive (MID).

Fibre-optic thermometers allow temperatures to be measured in all the cases mentioned above, but they suffer from cross-sensitivities to other quantities (e.g., strain, vibration, humidity). In order to exploit the full potential

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP

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Issued: July 2024

of fibre-optic sensors (e.g. Fibre Bragg Gratings (FBGs) in silica or sapphire fibres) or distributed sensing techniques (using Rayleigh, Brillouin or Raman scattering), it is necessary to investigate, minimise and quantify these cross-sensitivities so that reliable results can be obtained. Standards, calibration guides and services are required to integrate fibre-based thermometry into the existing energy system and infrastructure.

Objectives

The overall objective of the project is to develop a research, calibration and testing infrastructure for fibre-optic thermometry measurements. The specific objectives of the project are:

1. To develop accurate methods for quantifying the sources of measurement uncertainty and cross-sensitivities of existing fibre-optic thermometers. This includes (i) disturbance effects such as thermal expansion, strain, vibrations, humidity of surrounding air or pressure, (ii) ageing effects and (iii) the influence of sensor mounting.
2. To develop accurate and validated distributed temperature sensing (DTS) techniques for large scale applications, based on Rayleigh, Raman and Brillouin scattering or multiplexed fibre FBGs. Measurement uncertainty and spatial resolution will be determined for the DTS methods, with an expanded target uncertainty ($k=2$) of 3 °C up to 500 °C.
3. To develop validated fibre-based thermometry (e.g., FBG sensors) for harsh environments. These will include high temperature process control with an expanded target uncertainty of 3 °C up to 1600 °C and precise temperature monitoring at elevated temperatures (expanded target uncertainty 1 °C up to 700 °C).
4. Using the techniques developed in Objectives 1 to 3 to perform 12 case studies in key application areas for fibre-optic thermometry: (i) monitoring of electrical power cables and other parts of the grid, (ii) control of energy-intensive high-temperature processes, (iii) monitoring of the loading state of heat storage tanks, (iv) monitoring of geothermal heat storage, and (v) NMI intercomparisons. To provide validated information on suitable fibre-optic thermometry techniques for specific applications, specific temperature ranges, spatial temperature resolution and achievable measurement uncertainties.
5. To establish an integrated European metrology infrastructure with certified European training centres and accredited calibration laboratories for fibre-optic thermometry. This will include the development of testing and calibration guides. In addition, to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, certification and accreditation bodies), standards developing organisations (IEC) and end users (sensor manufacturers, industry and energy sectors).

Progress beyond the state of the art and results

This project will go beyond the state of the art by developing new and validating existing methods to identify and quantify sources of measurement uncertainty of various point-like fibre-optic sensors (e.g. silica/sapphire FBG, Fabry-Pérot interferometer) and for distributed temperature sensing techniques (using Rayleigh, Brillouin or Raman scattering) used in the metrology community and industry sector. Based on these findings, calibration routines will be developed and validated for different temperature ranges and applications. The measurement uncertainty of at least three different fibre-optic temperature measurement techniques will be metrologically determined (partly for the first time) and improved. The aim is to achieve low extended target uncertainties ($k=2$) in expanded temperature ranges beyond the state of the art: 3 °C at up to 500 °C for distributed temperature sensing (DTS), 1 °C at up to 700 °C for FBG and 3 °C at up to 1600 °C for sapphire FBG. Finally, the sensors will be tested in industrial case studies relevant to the European energy system.

Objective 1: Quantifying the sources of measurement uncertainty.

Several institutes around the world have carried out studies on the reliability of temperature measurements using fibre-optic sensors, but no validated SI traceable calibration of these sensors has been carried out in Europe. As a result of this careful literature review, promising fibres for this traceable calibration have been selected. This project will establish methods to investigate the specific effects for the different fibre-optic sensing methods and their influence on the temperature uncertainty. This will include the effects caused by thermal expansion, strain, vibration, ambient humidity and pressure, ageing effects and the influence of sensor

mounting position. Several set-ups to test for these cross-sensitivities have been designed and are under construction. The aim is to fill existing knowledge gaps regarding the causes of measurement uncertainties and to increase the reliability of fibre-optic sensors, in order to establish calibration routines for fibre-optic sensors.

Objective 2: Development and validation of distributed temperature sensing (DTS) techniques.

Existing calibration infrastructure and methods are designed for the needs of point-like temperature sensors. To fully exploit the benefits of fully distributed sensing, novel validation and calibration approaches are being developed with respect to measurement uncertainty and spatial resolution. In order to provide a traceable calibration of the range output of commercial DTS interrogators with uncertainties, a new calibration framework has been developed using a constructed fibre artefact. This will be used to determine the measurement uncertainty for a DTS method with an expanded target uncertainty ($k=2$) of 3 °C at up to 500 °C. An interlaboratory comparison will be performed to ensure the robustness of the validation. Furthermore, quasi-distributed point sensors (FBG) and distributed sensors (DTS) will be compared to determine performance differences.

Objective 3: Development of fibre-based thermometry for harsh environments.

This project will develop, validate and calibrate silica and sapphire FBG-based temperature sensing techniques for industrial conditions at high temperatures. FBG sensors in silica fibres are developed and will be characterised to achieve an expanded target uncertainty ($k=2$) of 1 °C at up to 700 °C with traceable calibration. The promising results of EMPIR 17IND04 EMPRESS2 with sapphire-based FBG sensors are improved to achieve an expanded target uncertainty of 3 °C at up to 1600 °C (compared to 10 °C at 1500 °C) and to meet industrial requirements. A novel prototype for the interrogation of sapphire FBG using an automated mechanical mode mixer has been developed and shows promising first results on the way to drastically reducing the uncertainty of these sensors. In addition, alternative approaches using modified sapphire FBGs with wavelengths around 800 nm, high-resolution Fabry-Pérot interferometers, and fluorescence-based fibre thermometers are investigated to overcome the lack of metrological validation. A new Fabry-Pérot temperature sensor has been developed whose design ensures an air gap between the encapsulation and the sensitive area of the fibre. This is expected to reduce the mechanical interaction between the sensor and the encapsulation, thus enhancing the high temperature reliability of these sensors.

Objective 4: Case studies in key application areas.

The project will carry out 12 case studies in 5 key application areas for fibre optic thermometry to demonstrate the practical use of traceable fibre-optic sensors in a wide range of applications, each with its own specific requirements, including (i) power cables and other parts of the electrical grid, (ii) energy-intensive high temperature- processes, (iii) heat storage tanks, (iv) geothermal heat storage, and (v) NMI intercomparisons.

For the first time, the operational status of high-voltage components will be demonstrated using a calibrated fibre-optic sensor at operating voltages of up to 100 kV. Fibre monitoring systems are currently being installed at high-voltage cable joints and first reference measurements are being carried out. Monitoring of high-voltage cables over many kilometres to improve electrical load management will also be carried out, and the defect analysis of transition joints will be investigated with unprecedented high spatial and temperature resolution (target 0.5 m and 0.1 °C).

Monitoring of energy-intensive high-temperature processes for glass and silicon production using sapphire FBG-based sensors at temperatures up to 1600 °C will be performed with improved accuracy, allowing advanced process optimisation.

The existing local electrical temperature sensors will be replaced by distributed and quasi-distributed temperature sensing solutions to monitor thermal storage systems, such as molten salt tanks. The fibre-optic sensors will cover a temperature range up to 500 °C and are expected to provide high-resolution temperature profiles needed to optimise storage efficiency.

The optimisation of seasonal geothermal heat storage with borehole depths up to 200 m using distributed temperature sensing will be investigated by studying the long-term stability of the sensors under operating conditions. In addition, methods will be developed to determine the effects of fibre ageing in existing borehole installations.

Several test sites have been established and their specific requirements for fibre optic temperature sensors have been collected. Examples include the molten salt storage tank at the MOSA facility in Spain, the

Skagenrak4 high voltage DC interconnector cable between Norway and Denmark, and specific industrial furnaces for glass and silicon production. Customised sensor solutions are currently being developed.

Finally, NMI intercomparisons between participants will be carried out to characterise the behaviour of sensors and readout units of different origins and to analyse systematic effects of the calibration infrastructure. This will provide the basis for future calibration services.

Outcomes and impact

The need for the project objectives was highlighted in the final report of the CIPM Task Group for Emerging Technologies in Contact Thermometry (CCT-TG-CTh-ET) to answer the question “What's holding back fibre thermometry?” The project was also presented to the EURAMET Technical Committee for Thermometry (TC-T) and the European Metrology Network for Climate and Ocean Observation (EMN-COO), as well as to 15 stakeholders in a discussion panel. Several other stakeholders have expressed interest and will be kept informed through a newsletter.

The need for the project and the importance of advancing fibre optic thermometry for the protection of critical infrastructure in the context of energy transition was presented in the last two editions of the German KRITIS (Security and Availability of Critical Infrastructures) Symposium in October 2023 and June 2024. The metrological testbench for distributed fibre sensing based on a fibre artefact was presented at an international workshop.

Outcomes for industrial and other user communities

Energy transmission networks are expected to benefit from the project. Better temperature measurements of power cables, transformer stations and other key components will lead to advanced load management of the European electrical grid. Fibre-optic sensor technology will enable the energy industry to manage the increasing demands on electrical infrastructure.

The project will develop and implement monitoring and control solutions for energy storage systems that have the potential to significantly minimise the downtime of solar and wind power. These solutions will improve the measurement of the thermal energy available in energy reservoirs based on molten salts or other materials by determining a distributed temperature profile rather than a single point temperature measurement. This will increase the efficiency of thermal energy storage and ensure operational safety by detecting local hot or cold spots and efficiency losses due to unwanted mixing.

The results of the project can also be used by the nuclear energy sector to improve measurements in areas that are difficult to access or have high electromagnetic fields that can interfere with measurements made with conventional temperature sensors such as thermocouples and platinum resistance thermometers.

To promote the uptake of the project, extensive engagement with a wide range of stakeholders will take place throughout the project. The training on novel methodologies planned within the project aims to promote early adoption of the technology by stakeholders (e.g. sensor and instrument manufacturers) to enable future competitive products and services.

A reliable European calibration infrastructure will enable a valuable market comparison between conventional (electrical) and optical temperature sensors. As a result, the use of calibrated fibre-optic sensors will increase.

Outcomes for the metrology and scientific communities

The development of guidelines and best practices will have a high impact on the metrology community, as it will create a higher degree of reproducibility between laboratories. NMIs will be able to work towards meeting the needs of project stakeholders as a natural part of the project. Improved and calibrated fibre-optic thermometry instruments will make them suitable for a variety of research fields, ranging from electrical engineering of power converters to optimisation of chemical production, where this type of temperature sensors is much less susceptible to errors caused by the harsh environment.

In order to promote the uptake of the results of this project by these communities, the consortium will invite them to participate in the project workshops and will further disseminate the results through the strong link between the project participants and the CCT and TC-T, as well as through conferences and open access publications.

Outcomes for relevant standards

The results of the project will be promoted to the standardisation community with the aim of incorporating the project results into standards. In order to achieve this, the participants will disseminate the results of the project to the working groups in which they are involved, such as IEC TC 86/SC, IEC TC 86C/WG2, SEAFOM, a forum promoting the growth of fibre-optic monitoring system installations in the oil and gas industry, the European Metrology Networks (EMNs) on climate and ocean observation, clean energy, and advanced manufacturing, and the CIGRE Council on Large Electric Systems. This will initiate the preparatory process for the development of new standards.

Longer-term economic, social and environmental impacts

This project will remove barriers to the widespread use of fibre-optic thermometry in various sectors by providing novel, traceable temperature measurement solutions where temperature measurement and control play a key role but are inaccessible to conventional electrical methods. This will make the energy infrastructure more resilient and reliable in the face of future challenges. In addition, this project will strengthen fibre-optic temperature measurement manufacturers and service providers in Europe.

A resilient and efficient energy supply is a key factor for the location of many industries. The necessary optimisation and monitoring of energy infrastructure is therefore essential to keep energy-intensive industries in the EU in the long term. This will enable the EU to achieve the desired increased economic independence. It will also help to improve the quality of industrial processes and reduce downtime, thereby reducing indirect costs and strengthening the EU economy in the global market.

Europe plays a key role worldwide in the field of fibre-optic sensors. The creation of new standards, the capability for traceable calibration of fibre-optic sensors and the penetration of these technologies into the wider society will enable an innovative industry to be maintained and expanded. This will create high quality jobs in sensor and instrumentation manufacturing and measurement application services.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2023, 36 months
Coordinator: Stephan Krenek, PTB		Tel: +49 30 3481 7745
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	11. BAM, Germany	20. APL, Spain
2. CEM, Spain	12. CEA, France	21. Engionic, Germany
3. CMI, Czechia	13. CIEMAT, Spain	22. FiSens, Germany
4. CNAM, France	14. Elkem, Norway	23. Hyme, Denmark
5. DFM, Denmark	15. FhG, Germany	24. SCHOTT, Germany
6. DTI, Denmark	16. IPHT, Germany	25. Statnett, Norway
7. JV, Norway	17. NORCE, Norway	26. VIAVI, France
8. LNE, France	18. TUB, Germany	
9. RISE, Sweden	19. UM, Slovenia	
10. UL, Slovenia		
Associated Partners: 27. CITY, United Kingdom		



Publishable Summary for 22NRM01 TraMeXI Traceability in medical X-ray imaging dosimetry

Overview

X-ray imaging is an important technique used in medicine however its use forms the largest component of exposure to artificial ionizing radiation. Consistent quantification of a patient's exposure to radiation with calibrated dosimetry equipment is essential to comply with Council Directive and ensure patient safety. Currently, the procedures used by calibration laboratories, based on relevant standards and international protocols, do not fully consider the recent technical developments in X-ray imaging. This project will perform a critical assessment of conditions applied in calibrations and study the performance of different dosimeters. Updated measurement and calibration procedures will be proposed for inclusion into standards and protocols.

Need

The medical use of radiation is well justified but due to the potential detriment to patients, the radiation doses must be optimised with regards to image quality as required in the Council Directive (2013/59/Euratom). To achieve consistent, comparable, and traceable measurement results, the dosimeters must be calibrated, measurement methods must be harmonised, and uncertainties must be estimated. According to IAEA TRS-457 a measurement uncertainty of 7 % with 95 % confidence level is considered appropriate in X-ray imaging dosimetry.

X-ray systems provide the option of adjusting their energy spectra so that image quality and patient dose can be optimised. Reference radiation qualities are used for calibrations (IEC 61267), however, currently these qualities do not cover the entire clinical range and thus, the traceability chain cannot be fully achieved.

Performance of dosimeters play an essential role in achieving the accuracy required in X-ray imaging practices. Requirements are defined based on limits of variation for the effects of influence quantities in IEC 61674. Currently it does not allow a clear distinction between reference and field-class dosimeters, nor take sufficiently into account the characteristics of the dosimeters that exist on the market today.

Semiconductor-based X-ray multimeters (XMMs) have become the most common dosimeters in use at hospitals. The response of a semiconductor detector has a pronounced energy dependence, but the manufacturers have created algorithmic corrections to overcome this challenge. However, in this case, it can be challenging to confirm the uncertainties and traceability of the measurements. In addition to radiation dose, these multimeters offer the possibility of measuring further quality control parameters. However, there are no agreed performance requirements or calibration guidance for these measurements.

In addition, there are no agreed or validated calibration or measurement procedures for these dosimeters. Thus, there is a need to establish basic metrological support for the new technology already being adopted in clinics.

Objectives

The overall objective of the project is to harmonise and standardise calibration and measurement procedures to ensure traceability and accurate dosimetry in medical X-ray imaging.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
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Issued: April 2024

1. To review a representative range of X-ray radiation fields relevant in medical imaging and, based on the outcome, to propose an update of reference radiation qualities. This provides input to the future revisions of IEC 61267 and IAEA TRS-457.
2. To investigate the performance of at least 8 different commercially available X-ray dosimeter types in at least 3 NMIs/DIs and 3 clinics using calibration and clinical exposure conditions. Based on the results, updated requirements for reference- and field-class dosimeters will be proposed to enable measurements with a targeted uncertainty of 7 % ($k=2$). This provides input to the future revisions of IEC 61674 and IAEA TRS-457.
3. To define a harmonised calibration procedure for X-ray multimeters (XMMs), and thus, to enable an unbroken traceability chain for measurements of relevant clinical parameters. This provides input to the future revisions of IEC 61676 and IAEA TRS-457.
4. To validate established and updated calibration procedures and related uncertainties identified in objective 3 for radiation fields as identified in objective 1, applied to different classes of dosimeters as identified in objective 2 by an international comparison.
5. To collaborate with the technical committees of international organisations, and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs, including the provision of a report on updated reference X-ray qualities and a calibration procedure for X-ray dosimeters and recommendations for incorporation of this information into future standards at the earliest opportunity.

Progress beyond the state of the art and results

Updated reference radiation qualities

A market analysis of the clinically available devices for medical X-ray imaging was carried out. The result is a table that links the available clinical devices with the corresponding radiation qualities for all modalities under investigation. This table will be analysed to find a representative set of reference radiation qualities.

In addition, a survey of the commonly used radiation qualities was conducted. The results were analysed to derive the limits of filtrations and generator voltages used in clinical practice. These results were summarized in a presentation at the M9 meeting. This information will be used to identify the most used radiation qualities in the table that resulted from the market analysis.

A protocol for clinical spectrometry was developed during several technical meetings. The protocol has been finalised and is available for all partners for spectrometry at clinical devices for medical X-ray imaging.

Requirements for dosimetry equipment

In the first reporting period an analysis of commercially available dosimeters and their performance characteristics was carried out. Current performance criteria and potential for classification of dosimetry equipment was retrieved from literature and existing standards, IEC61674, IEC60731, ISO/IEC63465, TRS398 and TRS457.

The minimum rated ranges of influence quantities defined in IEC 61674:2012 were compared with the conditions covered in the clinical practice. Based on this information, influence quantities that require extension and dosimeter properties which could be used for the classification of reference or field-class dosimeter were selected.

From the medical physics survey carried out in the clinical centres, 8 dosimeters were extracted as candidates for reference and field-type and will be measured according to a protocol agreed upon by the whole consortium. In this regard, benefiting from this systematic study and the exchange of metrological expertise between the partners, a test protocol was developed for the measurement of reference and field dosimeters. Convergence on a shared protocol is almost achieved and the consortium is ready to start a fruitful experimental campaign.

The newly defined reference-class dosimeter could be used at clinics to provide traceability. Based on this, a recommendation will be provided to IEC 61674 and to IAEA TRS-457 for including the classification of dosimeters based on their performance.

Calibration and measurement procedures for X-ray multimeters

The clinical relevance of quantities measured with XMMs has been assessed based on the data collected from the literature and surveys, and calibration procedures and traceability chain will be established for the most important quantities. Calibration procedures will be adapted for use in clinics, to allow performance checks of XMMs in clinical beams, and to estimate the impact of the differences between clinical beams and reference beams applied for instrument calibration. The obtained data will be used to recommend updates for IEC standards and IAEA TRS-457 for air kerma and practical peak voltage measurement devices, and to propose inclusion of additional quantities measured by the XMMs in IEC standards.

Validated calibration services

A comparison exercise will be organised to validate the newly developed radiation qualities and calibration procedures for XMMs. In addition, the response of field instruments in well-defined but slightly variable conditions at different calibration laboratories will be studied which will result in realistic data on actual variation of calibration coefficients provided to customers. During the first reporting period, project discussion took place and based on these, an overview-schematic of the comparisons and their requirements out at the NMI/DI was drafted. The comparisons exercise will take place in two rounds, each starting and ending at the repeating laboratory. The number of radiation qualities remain unchanged with respect to the protocol. No distinction will be made between reference class and field class XMMs.

Outcomes and impact

The project involved different stakeholder groups to ensure coverage of their specific needs and efficient implementation and dissemination of results. A stakeholder committee with 24 members was formed including members representing different stakeholder groups. Their interests were identified based on a questionnaire. Communication with the committee members has been active, and several meetings have been organised in virtual and hybrid formats. Their views and feedback have been collected to refine the technical work. A project web page has been developed and set up at <https://tramexi.com>. The website is updated regularly. To present the aims of the project, a flyer and poster, which include general information about the project, have been developed. The flyer and poster are available for download on the project website and have been shared through social networks. In addition, the project and its progress have been presented at three scientific conferences, two symposiums, and two workshops. The goals of the project have been presented to several metrology organizations and the Heads of the European Radiological Protection Competent Authorities. The project has been introduced to technical committees of standardization bodies (IEC, SESKO, NEN). Within the project, five technical visits have been organised among participating laboratories to discuss practical aspects of X-ray spectrometry, to measure X-ray spectra in clinics and calibration labs, and to provide training on clinical calibration and measurement protocols.

Outcomes for industrial and other user communities

The updated reference radiation qualities and calibration procedures developed in the project will enable calibration laboratories to improve their calibration services. These improved calibration services will support medical physicists and technical services performing dosimetry measurements by providing more useful calibration data for the end-user. The knowledge of dosimeter response over the clinically relevant range of radiation qualities and defined limits of variation will provide confidence for clinical measurements in varying conditions. This will also allow better understanding of the uncertainties involved. The guidance on measurement procedures recommended in the project will help performing consistent and comparable measurements. All these results together will enable the end-user to improve the accuracy of clinical X-ray dosimetry. The needs have been communicated with the experts of the BIPM, IEC, SESKO, IAEA HERCA, NEN, COOMET to enable good future implementation in the standards and codes of practice.

The data on dosimeter performance and harmonised and standardised procedures developed in the project will be referred by European and national regulators (such as STUK). This will enable regulators to have greater confidence in the calibration of dosimetry equipment and measurements for the implementation of legal requirements. A member of Herca (Heads of the European radiological protection competent authorities) was invited to the stakeholder committee to enable direct communication with the regulators.

The developed and improved calibration procedures will enable XMMs manufacturers to test their devices and provide comparable specifications in their manuals. This will improve the position of their products on the international market and integrate their products as a part of the dosimetry chain in an accurate and cost-

efficient way. Most of the XMM manufactures as well as a manufacturer of devices for X-ray imaging were invited to the stakeholder committee and the consortium has worked in close collaboration with them to enable good decisions to support the implementation of the proposed methods and standards. In addition, the European Trade Association representing the medical imaging, radiotherapy, health ICT and electromedical industries (COCIR) was contacted to initiate contact with all X-ray system manufacturers.

Different stakeholder groups, such as X-ray system manufacturers as well as medical physicists and technicians performing quality control measurements, are interested in the quality control related parameters of X-ray systems which can now be measured with the XMMs non-invasively. The developed calibration procedures for XMMs will enable these end-users to achieve traceable results for those quality control related parameters which do not currently have available standardised calibration services. The measurement reliability of these parameters will be improved when harmonised calibration procedures are established. A survey was run to collect the needs of end-users and this data will be used to define the target uncertainties and needs for the new calibration services.

Outcomes for the metrology and scientific communities

The project will publish recommended new reference radiation qualities (RRQs), a spectrum catalogue for RRQs and reference radiation qualities currently described in IEC 61267 on its website. These new reference radiation qualities can be established by other calibration laboratories to better cover the clinical needs. The need for this change has already been communicated with the metrology communities (EURAMET, COOMET, IAEA, BIPM, CCRI(I)). In addition, the spectrum catalogue can be used to compare spectra in different laboratories and estimate radiation quality related uncertainties.

Based on the discussion with calibration laboratories and the IAEA there is a need for reference class dosimeters. The definition of reference-class dosimeters for X-ray imaging will help dosimetry laboratories to categorise different levels of dosimeters and support their selection of appropriate metrological standards. In addition, this will support those who intend to perform measurements with improved accuracy. The study of the response of semiconductor-based detectors will consider the growing use of such instruments in clinical routine by providing improved procedures to ensure the traceability of such measurements. Ideally, the number of calibration points can be decreased which will reduce the workload of calibration laboratories and simplify the clinical measurement procedures.

In addition to updated calibration procedures for the radiation dose measured in terms of air kerma, the results will open new opportunities for dosimetry laboratories to offer calibration services for other quantities and parameters measured by XMMs. Traceable calibration of this equipment will provide additional confidence for quality control of clinical X-ray systems.

The project will carry out four international comparisons to validate the new proposed radiation qualities and the procedures to measure other parameters provided by the current dosimeters, the results of which will be published in the key comparison database (KCDB). This will allow the participating national metrology institutes (NMIs) or designated institutes (DIs) to amend their calibration and measurement capabilities (CMCs) and NMI's from all over the world to set up similar comparisons.

The established European Metrology Networks (Radiation Protection) will also provide valuable support for the dialogue between different stakeholders.

Outcomes for relevant standards

The research results provide relevant data for the updates of existing IEC standards such as IEC 61267, IEC 61674, IEC 61676, IEC 62220-1 and International Code of Practice IAEA TRS-457 and their future extensions and the consortium has been in close collaboration with the IEC and IAEA to keep them informed about the results of the project. Close cooperation with those standardisation organisations is emphasised to achieve international impact. The standards are used by different stakeholders especially by the companies.

The experimental and theoretical investigation on the characteristics of radiation qualities is ongoing and this allows the assessment of relevant radiation qualities that represent clinical conditions. As a result, it will be possible to identify reference radiation qualities that should be included in the IEC 61267, in the IAEA TRS-457 and used for calibrations. The IEC 61674 and IAEA TRS-457 defines the performance requirements for dosimeters and there are several IEC standards which define requirements for X-ray imaging devices (e.g., IEC 62220-1). They refer to the radiation qualities of IEC 61267 to specify limits of variation for dosimeters and X-ray imaging devices. The assessment of current requirements for dosimeters, existing performance data

and the needs in clinical practice has been started. As a result, all information will be compiled to provide a recommendation towards an update of IEC 61674.

Furthermore, after the evaluation of existing calibration and clinical measurement procedures for XMMs for air kerma and other measurement quantities and parameters (practical peak voltage, tube voltage, half-value layer etc.), updated procedures will be prepared and tested on a sample of XMMs. A method for traceable chain of calibration in terms of practical peak voltage and tube voltage will be investigated and proposed to IEC 61676 and IAEA TRS-457. In addition, new standards or update of existing standards are proposed to cover the other measurement quantities and parameters which are currently not covered by any standards.

Longer-term economic, social and environmental impacts

The calibration procedures developed in the project will provide European countries with a well-consolidated methodology for accurate calibration and verification of X-ray imaging dosimeters. Considering the specific focus on XMM technology and large number of XMMs in clinical use, this will have a significant scientific impact in medical X-ray dosimetry. The European metrology community will profit from this project, by acquiring improved knowledge in the field of X-ray dosimeter calibration, by increasing its influence when responding to an expanding demand related to the appropriate measurement of patient exposure and strengthened collaboration with industry.

The research will have a direct impact on the accuracy, consistency, and comparability of clinical X-ray dosimetry measurements. The proposed procedures will provide the best outcome at all levels to enable a traceability chain and harmonised calibration procedures for dosimeters worldwide. The improved procedures will increase the European influence on the global market. Finally, this will provide a benefit to a large number of patients through a reliable quality assurance of X-ray imaging.

List of publications

Kojić, A. et al (2024) 'Influence of anode/filtration setup on X-ray multimeter energy response in mammography applications', Radiation Measurements p. 107135. Available at <https://doi.org/10.1016/j.radmeas.2024.107135>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		June 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. STUK, Finland	9. EEAE, Greece	-
2. CMI, Czechia	10. HUS, Finland	
3. ENEA, Italy	11. INM, Moldova	
4. IMBiH, Bosnia and Herzegovina	12. OPBG, Italy	
5. IST, Portugal	13. SKBS, Germany	
6. PTB, Germany	14. VINS, Serbia	
7. TENMAK, Turkey		
8. VSL, The Netherlands		

Publishable Summary for 22NRM02 STANBC

Standardisation of Black Carbon aerosol metrics for air quality and climate modelling

Overview

Black carbon (BC) is an air pollutant that contributes to climate forcing, reduced crop yields and impacts on our health. Produced by incomplete combustion of transport and other fossil fuels, air quality networks have been set-up to monitor its mass concentration and legally binding procedures are in place to identify and treat emission sources. Networks measure equivalent Black Carbon (eBC) mass concentrations in real time with light absorption photometers, but traceability is incomplete, uncertainties are poorly understood, and robust documentary standards are lacking. This project will address these needs and via input into normative standards aims to generate greater reliability for measurements of this important air pollutant.

Need

Carbonaceous particles continue to receive high levels of attention from the scientific community and policy makers, because of their role in both climate change and health effects. The dominant sources of Black Carbon have changed over the decades, with modern emissions arising from vehicle combustion emissions, forest fires, wood and biomass burning. Black Carbon has been identified as an important climate-forcing agent, contributing to atmospheric warming due to its much shorter atmospheric lifetime than CO₂. Mitigation strategies for BC could rapidly slow the rate of climate change. Without a reliable measurement infrastructure from the NMI level to field-based measurements supported by underpinning CEN standards upon which legislation can rely, the European vision for a toxic-free environment and climate neutrality will not be put into practice. This project will contribute to the developments of such standards (Objective 4).

The mass concentration of airborne particles loosely described as black carbon has been widely measured by various optical methods since the early 20th century, with hundreds of filter-based optical absorption photometers now installed at European aerosol-monitoring sites due to their portable and robust design. However, these are notorious for their high measurement uncertainties, estimated to be up to 400 % for eBC mass concentration. These uncertainties depend on the aerosol properties at the measurement location. As a result, field measurements at different monitoring sites are often not comparable and it is difficult to extract meaningful long-term data. To overcome these limitations, there is need to determine methods for calibrating filter-based light absorption photometers (Objective 3) using the in-situ reference methods developed in Objective 1 and the parameters for conversion of the optical measurements into mass (Objective 2).

Objectives

The overall objective of the project is to establish a sound measurement framework for both aerosol light absorption coefficient and its conversion to eBC mass concentration, bringing traceability and consistency to both, and consequently making measurements across different air quality monitoring networks in Europe (and worldwide) more accurate and comparable.

The specific objectives of the project are:

1. To develop traceable in situ reference methods for aerosol light absorption coefficient (extinction minus scattering and photo-thermal interferometry) with a robust uncertainty budget estimation as a function of the light wavelength and ambient aerosol properties (e.g, single scattering albedo SSA) suitable for

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

use in generating a calibration chain to instruments used to monitor environmental levels of BC. Target measurement uncertainties for the reference methods are $\leq 10\%$. In addition, to provide clear guidelines to end users about the specifications, limitations and application range of each reference method.

2. To determine traceable methods for the measurement of the aerosol mass absorption cross-section with a robust uncertainty budget estimation at various wavelengths based on traceable measurements of light absorption and EC mass. In addition, to establish the relationship between eBC mass, rBC mass and EC mass (EN 16909:2017) via inter-comparisons.
3. To determine methods for calibrating filter-based light absorption photometers using the *in situ* reference methods developed in Objective 1 and a series of well-defined synthetic aerosols generated in the laboratory. The SSA of the synthetic aerosols will span the whole range (from < 0.5 to almost 1) to determine SSA-dependent calibration factors, including multiple scattering factors with the associated measurement uncertainties (target uncertainties are $< 15\%$ for 95 % confidence level).
4. To contribute to the development of a new CEN standard on i) traceable reference methods for determining aerosol light absorption coefficients (i.e. at multiple wavelengths) and ii) materials and methods for calibrating filter-based photometers against the reference method(s). This should include close collaboration with CEN/TC 264, CEN/TC 264/WG 35 and ISO/TC 146/SC 3.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g. accredited laboratories), standards developing organisations (e.g. CEN/TC 264, CEN/TC 264/WG 35 and ISO/TC 146/SC 3) and end users (e.g. national and international climate and air quality monitoring networks, instrument manufacturers), and to disseminate to the wider stakeholder community via the European Metrology Network (EMN) for Climate and Ocean Observation, EMN Pollution Monitoring and national and European air quality monitoring networks (e.g. ACTRIS, EMEP, GUAN, NABEL, UK Black Carbon Network, Atmo-France, FMIO DATA) and instrument manufacturers.

Progress beyond the state of the art and results

The current state-of-the-art is that black carbon measurements are being widely made based on a principle that has been used for many decades, with one of several designs of filter-based instrument, such as multi angle absorption photometers (MAAP), aethalometers and other particle absorption photometers. These instruments do not measure BC mass concentration directly; they determine light attenuation as it passes through the filter with the sample, convert it to the absorption coefficient based on several assumptions, and calculate the so-called equivalent BC (eBC) mass concentration with the use of a fixed MAC value.

Due to recent developments within the EMPIR 16ENV02 Black Carbon (2017-2020) and other EU projects, there are now traceable techniques that measure aerosol light absorption while the particles are airborne, and these of course are not complicated by the effects of filter-based measurements. Studies are clarifying the corrections needed to obtain accurate aerosol absorption coefficients and eBC mass concentration from filter-based instruments by inter-comparisons with reference methods, but further work is needed. The corrections can be made more valuable by including more detailed information on the particles (e.g. light scattering properties, particle size etc.).

The technical results that are expected from this project are as follows:

Objective 1. Standardisation of traceable, primary methods for determining aerosol light absorption coefficients at multiple wavelengths of the light source

Traceable calibration procedures based on absorbing gas NO₂ and nigrosin particles were developed. NO₂ calibration uses a mobile permeation source to produce NO₂ with the precise amount fraction in the carrier gas traceably to primary standards. Gas absorption is calculated from the overlap of high resolution NO₂ absorption spectrum with the emission spectrum of light used for the measurement. Calibration with nigrosin particles is based on known refractive index and the selected size of monodisperse particles. Particle size selection using centrifugal particle mass analyser and electrostatic classifier in series is proposed. Mie calculation is then performed using mass equivalent diameter and measured particle number concentration to produce absorption coefficient at the desired wavelength. Nigrosin enables calibration in the whole visible and near infrared spectrum while NO₂ calibration is limited to the visible part. Both calibration methods agree better than 10%.

Transfer of calibration from primary to secondary standard is performed using nebulized CAB-O-JET200 because of its monotone spectral dependence of absorption.

Objective 2. Standardisation of methods for the determination of the aerosol mass absorption cross-section (MAC)

MAC is not a constant but depends on various BC aerosol properties. The dependency of MAC on particle size and aerosol mixing state was systematically investigated in the laboratory using different core sizes of miniCAST generated soot particles coated with organics. Various methods for measuring the light absorption coefficient (extinction minus scattering, filter-based light absorption, photothermal interferometry, photoacoustic method) and various methods for determining the carbon mass (thermography method, incandescent light method) were applied. For coated soot particles, the total mass and the organic mass were measured in addition to the coating thickness from SP2. The dependency of MAC values on aerosol characteristics was compared with the Mie-model successfully. The results will provide a unique set of MAC values that can be used to convert aerosol light absorption reported by filter-based absorption photometers into eBC mass concentration – an important step for using BC mass concentrations in the context of air quality.

Objective 3. Protocol for the lab-based calibration of filter-based absorption photometers

Calibration of filter-based absorption photometers has only been performed for a small subset of relevant aerosols (i.e. aerosols with low SSA) and is not yet standardised. The calibration procedure will be extended to include more environmentally relevant reference aerosols, covering the whole aerosol SSA range (i.e. from almost 0 up to about 1). This step is important to enable traceable measurements at monitoring stations in completely different environments, spanning from highways in urban agglomerations to the remote Antarctic. The consortium has been working on the preparation of a measurement campaign to take place at METAS in May-June 2024, where different test aerosol mixtures will be used, including bare soot particles and three different aged aerosols, prepared by mixing soot particles with secondary organic and inorganic aerosols.

Objective 4. New CEN TC 264 standard

Currently, no normative standard exists on BC-related metrics. The consortium will initiate a new Working Group (or Subgroup of WG 35) within CEN TC 264 dedicated to the standardisation of aerosol light absorption and eBC mass concentration. The results of this project will feed directly into the new standard, so completing the required measurement infrastructure to support the (NEC) Directive (2016/2284/EU) and the revision of the Air Quality Directive from 2008. A project survey has been done to identify potential stakeholders. A stakeholder questionnaire about metrology needs for black carbon determination is being prepared and will be circulated among the stakeholder community.

Outcomes and impact

The project's outputs have been presented in different conferences including the following:

- European Aerosol Conference 2023.
- 13th ICCPA International Conference on Carbonaceous Particles in the Atmosphere

Consortium members have participated in standardisation committee meetings including the following:

- ISO TC24 SC4 Particle characterisation
- Slovenian Institute for Standardization meeting

The issues of climate change and air pollution are truly international. Per unit of mass, black carbon has a warming impact on climate that is 460-1500 times stronger than that of CO₂, which makes its monitoring and mitigation important for early reductions in current global warming predictions. The breadth and depth of the challenges that need to be overcome to provide traceability for BC-related optical and mass concentration measurements require an extensive range of expertise. The scope of this project is therefore beyond the capabilities of a single NMI and a pan-European approach is essential in order to deliver the work.

Normative projects tackling global challenges, such as pollution and its detrimental effects on public health, must achieve wide consensus in order to harmonise procedures in Europe (and worldwide). They rely therefore by nature on the close collaboration between countries and the will to align national regulations. The EPM programme, bringing together NMIs, research institutes, instruments manufacturers and experts from air quality monitoring networks across Europe, is the ideal platform for the work described in this project.

Outcomes for industrial and other user communities

The EMPIR 16ENV02 Black Carbon and 18HLT02 AeroTox projects have greatly contributed to the development and characterisation of novel aerosol instruments (including a soot generator, the oxidation flow reactor known as OCU, and the photo-thermal interferometer PTAAM-2 λ). All these are manufactured in Europe and will be employed in the calibration procedure for filter-based absorption photometers either as reference aerosol sources or as reference measurement methods. Moreover, several manufacturers of filter-based absorption photometers are based in the EU. This project will enhance the end users' confidence in these instruments through standardisation, promote sales and help European manufacturers assume a leading role in the global market.

Outcomes for the metrology and scientific communities

The direct impact of the proposed research will be more accurate and more comparable measurements of aerosol light-absorption coefficient and better estimates of eBC mass concentration than in the current status of the widespread aerosol monitoring networks in Europe, through the standardisation of traceable methods for calibrating filter-based absorption photometers.

Indirectly, the impact would be very widespread. In terms of scientific benefits, the improved measurements would fit into EU atmospheric aerosol projects, refining climate change models, and improving the quality of conclusions from cohort health studies looking at the health effects of air pollution. Air quality measures to reduce human exposure to BC such as emission reduction and low emission zones have already been taken.

However, traceable BC-related metrics to reliably quantify the success of these measures are not yet available. The results of this project will feed directly into national air quality monitoring networks across Europe. The improved measurement accuracy will also help set up reliable black carbon emission inventories.

Outcomes for relevant standards

Currently, there are no legislated limits for BC for outdoor air concentrations, only the total mass of fine particles is regulated. This is partly due to the fact that there is no well-defined metric for BC mass concentration in ambient air. Ultimately, the project will provide a CEN standard on BC-related metrics and form the basis for future European legislation.

Longer-term economic, social and environmental impacts

According to WHO "...air pollution imposes a large economic cost on the countries of the WHO European Region. As at 2010, the annual cost of premature deaths from air pollution across the countries of the WHO European Region stood at EUR 1.4 trillion, and the overall annual cost of health impacts from air pollution stood at EUR 1.6 trillion". Thus, even a small decrease in health effects from air pollution would lead to substantial economic benefits.

Moreover, the effects of climate change can be expected to reduce the global economic output by 2050 for 11 % to 14 % compared with growth levels without climate change. That amounts to as much as EUR 23 trillion in reduced annual global economic output worldwide as a result of global warming. Though long-term warming is dominated by CO₂, the reduction of short-lived climate forcers, such as black carbon, can contribute significantly to limiting warming to 1.5 °C above pre-industrial levels. Unlike CO₂, which can stay in the atmosphere for hundreds of years, black carbon only remains there for up to two weeks. This means that efforts to reduce it would bring "immediate benefits" for the climate (and human health), according to the Climate & Clean Air Coalition, a United Nations initiative. Mitigating the results of climate change through BC reduction could lead to economic benefits in the order of billions of Euros.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2023, 36 months	
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Chief Stakeholder Organisation: JRC		Chief Stakeholder Contact: Jean-Philippe Putaud	
Internal Beneficiaries: 1. PTB, Germany 2. FMI, Finland 3. JSI, Slovenia 4. LNE, France	External Beneficiaries: 5. Haze, Slovenia 6. NCSR Demokritos, Greece 7. TROPOS, Germany	Unfunded Beneficiaries: -	
Associated Partners: 8. FHNW, Switzerland 9. METAS, Switzerland 10. NPL, UK 11. NRC, Canada			

Publishable Summary for 22NRM03 MetHyTrucks

Metrology to support standardisation of hydrogen fuel sampling for heavy duty hydrogen transport

Overview

Hydrogen can significantly contribute to reducing emissions from the transportation sector as it is particularly well suited as a fuel for long-haul heavy-duty (HD) vehicles. The uptake of hydrogen for heavy-duty transport requires further standardisation to support Europe's green energy future. Sampling systems and methods have already been developed for use at hydrogen refuelling stations (HRS) for light-duty (LD) vehicles, however there is a lack of technical evidence for heavy-duty transport. This project will deliver the evidence needed for the standardisation of hydrogen fuel sampling for heavy-duty applications. This will include the development of dedicated sampling systems for contaminants (gaseous species and particulate matter), methodologies for the validation of sampling methods, guidelines for the evaluation of sampling representativeness, uncertainty budgets, safety considerations and venting protocols. The outputs will be directly fed into ongoing standardisation activities in CEN/TC 268 and ISO/TC 197.

Need

With increased interest in using hydrogen and fuel cells in medium and heavy-duty applications, the need for dedicated standards for these applications has increased. Currently the number of hydrogen-fuelled buses, trucks and trains in Europe is around 500 units, but this is expected to increase at a very high pace. At least 60,000 hydrogen-fuelled trucks are expected to be in operation by 2030 which will require a large infrastructure comprising truck-suitable hydrogen refuelling stations.

Hydrogen-powered vehicles require extremely pure hydrogen as some contaminants can reduce the performance of the fuel cell even at very low levels. Previous metrology projects have paved the way for the development of the European quality infrastructure for hydrogen conformity assessment. However, the reliability of a measurement is intrinsically linked to the representativeness and reliability of the sampling itself. Poor sampling may lead to a fleet of HD vehicles being damaged. Moreover, standardisation is required as the HD-HRS network will be shared between operators (e.g. BP, Air Liquide, MotiveFuels). Also, sampling practices should not create a source of discrepancies in quality within the emerging network.

Within ISO/TC 197/WG 33, a new standard is being developed to support hydrogen sampling at hydrogen refuelling stations. Sampling is not currently standardised, and only good practice information is available in Annex K of ISO 19880-1. The new draft ISO 19880-9 standard is focussing on sampling for passenger LD-HRS due to the lack of technical evidence and sampling systems for HD-HRS. The main barrier is the lack of sampling systems, which are adapted for heavy-duty applications. Reliable specific sampling systems for HD-HRS need to be developed for both gaseous and particulate phases (Objective 1).

New or adapted sampling approaches, for HD-HRS applications, will need to be trialled in real conditions to assess the performance of the sampling approach. Without this data and evidence, standardisation documents for HD-HRS applications cannot be progressed. This will require a standardised protocol to meaningfully demonstrate sampling system performance (Objective 2).

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

An additional challenge will be to create the uncertainty budget associated with the sampling. This will be needed to assess the total uncertainty budget for the hydrogen quality assessment. This uncertainty budget will be directly linked to the representativeness of the sample collected (Objective 3).

Finally, the sampling of hydrogen at HRS is performed within an explosive atmosphere area. Therefore, there are associated safety risks. Consequently, the safe performance of hydrogen sampling needs to be considered (Objective 4).

Objectives

The specific objectives of the project are:

1. To develop three reference methods/systems based on new hardware for interfacing relevant nozzle geometries for hydrogen heavy duty applications. This includes addressing methods for both gaseous and particulate phases. In addition, method comparison with existing methods for sampling for light duty applications will be documented to demonstrate equivalence or identified bias.
2. To develop methodologies for the validation of sampling systems. This includes method validation, including evidence of the impact of physical parameters (e.g. pressure and flow) on sampling representativeness. Gas sampling validation includes accurate gas contamination and an assessment of the recovery yield. The system will be laboratory based for flexibility in fluid physical parameter control and gas composition.
3. To develop guidelines for the evaluation of the uncertainty of the sampling and for the sampling representativeness including the minimum sample size (target uncertainties of 10 %), and sample volume/gravimetric requirements by performing repeated samplings under varying conditions.
4. To support the standardisation of the safe heavy-duty sampling of hydrogen: including the venting of hydrogen, risk assessment and the training of stakeholders.
5. To contribute to the standards development work of the technical committees CEN/TC 268 and ISO/TC 197 to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who should use them, and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Methods for sampling hydrogen for quality assessment (gaseous species and particulates) at heavy-duty HRS (Objective 1)

This project will adapt existing, or develop new, sampling systems for HD applications. This is the first step that will be needed to enable the collection of a representative sample of hydrogen at these emerging stations. Several engineering companies (e.g. ENGIE, ZBT) will develop sampling systems to fill the market gap and the NMIs will ensure that the metrological aspects needed for the validation of these systems have been considered. The new sampling systems will be tested and validated leading to the development of guidance on the metrological testing and validation of systems for heavy-duty HRS sampling.

So far, two sampling systems for gaseous species have been adapted to the HD conditions by ENGIE and ZBT. A third sampling system has been designed and built, but some issues need to be addressed before it is fully functional. Key information regarding current and future specifications and operations of HD-HRS have been acquired via a questionnaire that was sent out to several stakeholders. Five completed questionnaires were received and collated. Another questionnaire was sent out to stakeholders to enable the review of LD sampling systems and what would be needed to adapt these to HD conditions. An open-access report was written, which discusses the parameters that affect the material compatibility of the sampling vessels. A general conclusion is that more studies are needed in order to better understand the effects of all of these parameters, specifically for the filling pressure and the temperature.

Methodologies to validate the sampling systems to ensure sample representativeness (Objective 2)

This project will develop a protocol to validate sampling systems. The first version will take advantage of all of the knowledge that has been gathered during previous projects (EMPIR projects 16ENG01 MetroHyVe and 19ENG04 MetroHyVe 2, and FCH-JU HYDRAITE). The outcome of this project will allow the consortium to

finalise the protocol using feedback from the activities conducted throughout this project. Finally, to enable the validation of all of the performance parameters of the sampling system, the project will provide a recommendation that can be used to assess the performance of sampling systems with regards to recovery in an environment where accurate gas contamination can be prepared. This will allow the consortium to establish documented evidence which proves that a given sampling method meets the requirements for its intended purpose.

The consortium published an open-access report summarising the literature and publications on existing protocols and guidelines related to the validation of the hydrogen sampling systems that are used for off-line quality control at HRS, including those developed in EMPIR JRP 16ENG01 MetroHyVe and 19ENG04 MetroHyVe 2, and in other relevant projects. Key information, regarding the protocols used and the experiences gained during sampling, has been acquired via a questionnaire that was sent out to several stakeholders and participants. Six completed questionnaires were received and collated.

Guidelines for sample representativeness and measurement uncertainties arising from sampling (Objective 3)

The current practice for assessing hydrogen purity, according to ISO 14687, involves sampling. The measurement uncertainty associated with the sampling is the single most important parameter that describes the quality of the measurements and it must inevitably contribute to the uncertainty associated with the reported result. While existing guidance identifies sampling as a possible important contribution to the uncertainty of a result, procedures for estimating the resulting uncertainty are not well developed and further specific guidance will be developed in this project.

The consortium published an open access report summarising the most relevant information from the Eurachem/EUROLAB/CITAC/Nordtest Guide on measurement uncertainty arising from sampling. Two main approaches for estimating the uncertainty associated with sampling are described; the empirical approach which uses some level of replication of the whole measurement procedure to give a direct estimate of the uncertainty for the final result of the measurement, and a modelling approach which identifies all of the sources of uncertainty.

Good practice guide for hydrogen venting during a sampling exercise (Objective 4)

The sampling of hydrogen fuel at a HRS is an operation within an explosive atmosphere (ATEX) area involving safety risks, which include a venting step. The sampling exercise is not part of the normal procedure that occurs at a HRS. As HD-HRS operate at high flowrates and downtime has to be minimised (to reduce the impact on the refuelling of trucks), safety is a key element for the standardisation of sampling. To reduce the risk to an acceptable level, a reliable risk assessment methodology will be prepared so that appropriate control measures can be planned and required safety standards can be established.

The consortium published an open access report regarding the safety and venting requirements for the different hydrogen sampling strategies which gathers the main sampling techniques and the venting procedures that are being used in the field during a HRS. It also provides guidelines for performing safe venting after the sampling.

Outcomes and impact

To promote the uptake of the sampling systems that are being developed in this project, and to share insights generated throughout the project, results were shared with scientific and industrial end-users. Two presentations were made at conferences, an oral presentation and a poster at the International Conference on Measurements of Energy in Germany in September 2023 and a poster presentation at the Gas Analysis Event in January 2024. The project was introduced to the ISO/TC 197 Hydrogen technologies WG27/28 and WG33. The project was also introduced to the GERG network. One paper has been submitted to Energy Reports.

Outcomes for industrial and other user communities

This project's outcomes will enable fit-for-purpose hydrogen sampling services to be used by industries, testing laboratories, research organisations and other end-users. End-users will be able to rely on hydrogen purity assessments, which will in turn contribute to preventing serious damage to hydrogen-powered trucks and buses and it will secure and improve the overall European quality infrastructure for hydrogen conformity

assessment. Considering the existing fleet of 500, and a future fleet of 60000, vehicles, it is critical to ensure that hydrogen fuel will not reduce vehicle lifetime, increase the cost of ownership significantly and the availability of the service for the early adopter communities. Maintaining a high level of service will be key for the successful energy transition towards green energy and lower CO₂ emissions.

The project's dissemination activities will enable the uptake of the outcomes by industrial stakeholders including HRS operators, fuel cell electric heavy duty vehicles, fleet operators, hydrogen producers, testing laboratories, research institutes and other end-users as well as standardisation committees.

The project's outcomes will contribute to lowering the detrimental impact of transport-related air pollution on the climate and health via extended implementation of hydrogen mobility.

As outlined above, it is anticipated that a major outcome of this project will be the widespread uptake and use of the sampling systems developed in the project throughout Europe and globally. Another outcome will be the increase in new services for hydrogen quality monitoring using the new solutions developed in this project. Due to the close collaboration between the participants and industrial stakeholders, the industry will be able to use the services developed in this project (new capabilities to sample hydrogen at HD-HRS) to demonstrate that the hydrogen they deliver has the required quality. Eventually, the industry will also be able to use the design of the sampling systems developed in this project to build their own sampling systems for internal use.

Outcomes for the metrology and scientific communities

This project will deliver protocols and guidelines to enable the metrological community to obtain an insight into the actual challenges associated with representative sampling. This will allow tailored sampling systems to be developed and validated.

The successful delivery of the project will significantly advance the scientific state-of-the-art by providing newly developed sampling systems that will be capable of collecting representative and thus reliable samples of the hydrogen delivered at the station. This will be a key tool for the hydrogen quality assessment chain. These developments will be brought to the metrological communities through workshops, webinars and other dissemination activities.

Gas metrology and commercial gas analysis laboratories will be able to use suitable sampling strategies at heavy duty refuelling stations to ensure that representative samples of hydrogen can be taken and transported to their laboratory.

NMIs having developed traceable and reliable methods for hydrogen quality assessment will be able to expand their services to the sampling of hydrogen at HRS. Whilst these new capabilities will support industry, the science community such as universities or laboratories will also benefit from the outcomes regarding the representativeness of a sample. The NMIs and DIs will provide metrological traceability from the nozzle at the HRS to the laboratory for hydrogen quality assessment as required for safe and reliable distribution of hydrogen at the HRS. This will address the demand for renewable energy and it will enable society to prepare for the energy transition.

Outcomes for relevant standards

The project's outcomes will provide direct input to several working groups within TC 197: WG 24, WG 29, WG 27, WG 28 and WG 3. This project is of most relevance for ISO/TC 197/WG 33 "Sampling for fuel quality analysis" as it will provide direct input on the results of the project to be considered for use in the development of the first revision of ISO 19880-9. This project will also liaise with the standards developing organisations that are responsible for EN 17124, EN 17127, ISO 19880-8, ISO 19880-1, ISO 21087 and ISO 14687.

This project will also provide input to the activities of other technical committees, such as BIPM WGFF, EURAMET/Metchem SC-GAS, and national working groups and mirror committees. In addition, the project's outputs will be disseminated to the European Metrology Network (EMN) for Energy Gases as several participants are active members of this EMN. Sampling representativeness and the evaluation of uncertainties, due to sampling, will also be important for gases other than hydrogen and some of the outcomes (for example the guidelines on sample representativeness) of this project will be used in other fields (e.g. biomethane).

Longer-term economic, social and environmental impacts

In addition to supporting long-term climate change targets, hydrogen buses and heavy-duty vehicles will improve air quality and provide health benefits as only water is emitted from the tailpipes; this will prevent people from breathing in carbon dioxide and carbon monoxide emissions and it will reduce the frequency of

pollution peaks. As more heavy-duty HRS are built, the number of Fuel Cell Electrical Vehicles (FCEVs) will increase. Then they will become more visible to society. However, as for any new market, public safety needs to be guaranteed and acceptance needs to be obtained. These can only be achieved by minimising operational problems, which will in turn be achieved by confidence and assurance that the hydrogen fuel has the required quality. Performing representative sampling is of paramount importance for the quality assessment. As enhanced acceptance of FCEVs is achieved, these vehicles will be more and more regarded as normal road vehicles rather than as a prototype or a small fleet. Societal acceptance of hydrogen fuel is essential to achieve the energy transition towards a greener society. As mentioned in the strategic agenda from the EMN for Energy Gases, it is clear that the electricity grid alone cannot support user energy demands. Moreover, diversification by the development of hydrogen technology would allow society to absorb a shock in a major energy input.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2023, 36 months	
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Chief Stakeholder Organisation: ITM Power Plc		Chief Stakeholder Contact: Nick Hart	
Internal Beneficiaries: 1. RISE, Sweden 2. Cesame, France 3. CMI, Czechia 4. PTB, Germany 5. VSL, Netherlands		External Beneficiaries: 6. ENGIE, France 7. GERG, Belgium 8. SINTEF, Norway 9. ZBT, Germany	
		Unfunded Beneficiaries: -	
Associated Partners: 10. NPL, UK			

Publishable Summary for 22NRM04 e-TRENY

Metrology support for enhanced energy efficiency in DC transportation systems

Overview

DC railway and metro systems, that are supplied by unidirectional substations, demonstrate a significant waste of energy due to their inability to fully recover the energy produced by electric braking. Bidirectional substations and/or storage systems are expected to significantly improve energy efficiency, but current equipment and procedures lack a determination of the actual overall efficiency performance as well as the efficiency of components e.g. power transformers and converters. In order to address these issues and the needs expressed by IEC TC9, CENELEC SC9XC and CENELEC TC14, this project will develop new methodologies for DC transport efficiency determination, that combine accurate on-site measurements with circuit models of the railway electric system.

Need

The transport sector, in particular road vehicles, is responsible for almost one quarter of Europe's greenhouse gas emissions. The modal shift to public transport with electric rail as a backbone (urban rail in urban areas) is a priority, and the EU policy to support the development of sustainable and smart mobility will lead to a consequent increase of energy consumption by electric rail transport. However, a major weakness in the efficiency of DC transportation systems is the limited recovery of the electric energy generated during the electrical braking of the trains. Estimates show that up to 1 GWh per year, about the annual consumption of 365 families, can be wasted in one single commuter line.

This situation can be significantly improved by the introduction of bidirectional power converters and storage systems that allow the injection of the braking energy into the upstream AC grid or in the local storage system. However, before this can be rolled out widely, electric transport operators, supply designers and developers need standardised methodologies and procedures that support substation procurement and allow accurate and reliable evaluation of the actual efficiency of power transformers and converters and system energy saving under real operating conditions. This is needed in order to verify the compliance with the designed efficiency and to quantify the cost/benefit ratio in a more realistic way.

CENELEC/TR 50646 has declared standardisation needs for the traceable determination of efficiency for different operation modes (traction, regeneration) and the determination of the performance of harmonic compensation on AC and DC side. With the increased efficiency of modern power converters and power transformers, CENELEC TC14 has also called for on-site determination of their losses under actual operating conditions, which requires accurate and traceable measurements. In addition, accurate loss determination under real operating conditions requires new and improved traceability that includes distorted and dynamic conditions.

Objectives

The overall objective of the project is to support enhanced energy efficiency in DC railway systems, via new traceable methods for on-site measurement of the efficiency of substation transformers and converters and for measurement of the efficiency increase achieved by the adoption of energy recovery systems such as non-conventional bidirectional substations or energy storage systems in commercial service.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership

Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: May 2024

The specific objectives are:

1. To provide an overview on possible configurations for non-conventional DC substations (e.g. bidirectional and/or with storage systems) including evaluation of pros and cons. To perform a survey of real installations focusing on the design characteristics and the expected or declared energy savings. To establish a suitable measurement approach and to design instrumentation for on-site measurement campaigns.
2. To develop a metrological infrastructure for calibration of high voltage (3 kV) and high current (1000 A) DC transducers and measurement systems under dynamic conditions with typical timescales from a few hundreds of milliseconds to a few seconds.
3. To develop, calibrate and apply on-site setups and algorithms for the measurement of the energy losses of non-conventional AC/DC substations and the charge-discharge efficiency of electric storage systems with an overall on-site target uncertainty of 10 % of losses. The setups allow capturing signals from DC to 20 kHz to perform Power Quality and transient event analysis.
4. To develop, characterise and determine the accuracy of a hybrid method based on the combination of field measurements and models for the determination of the energy saving provided by the upgraded DC supply system in real operating conditions.
5. To contribute to standards development of technical committees CENELEC TC9X, CENELEC TC14 and IEC TC9 aligning project outputs to their needs, with rapid communication including to final users (e.g. DC transportation system operators, manufacturers, designers).

Progress beyond the state of the art and results

1. *To provide an overview on possible configurations for non-conventional DC substations including evaluation of pros and cons. To perform a survey of real installations focusing on the design characteristics and the expected or declared energy savings. To establish a suitable measurement approach and to design instrumentation for on-site measurement campaigns.*

The standards in-force on power converters for DC railway supply currently only deal with AC/DC diode-rectifier systems. Such standards state that “If the purchaser requires measurement of the losses this shall be mentioned in the procurement specification. The current admissible tolerance for losses is +10 % of the guaranteed value”. However, the standards give very little information about the accuracy of the measurement chain for losses; for example, only detailed information is provided only for 50/60 Hz power component measurements. For losses lower than 3 % (efficiency > 97 %) the standard proposes a calorimetric approach which is time-consuming and cannot be implemented on-site. This project will go beyond this state of the art by in-situ accurate and traceable efficiency determination.

This project will develop a new traceable measurement infrastructure able to measure on-site the losses of conversion systems (power transformers, power converters, storage systems) during commercial service in two test cases, (i) on the metro and (ii) tramway line. Losses of AC/DC, DC/AC DC/DC and power transformers will also be determined with an overall target uncertainty better than 10 % of losses. This uncertainty is intended to allow reliable loss determination even for losses value lower than 3 %. The system will also enable the correlation of the efficiency and signal distortion up to 20 kHz. So far, the project has developed a setup for the generation of 3 phase voltage and current signals with maximum current of 100 A and maximum voltage of 100 V. The system can generate signals with arbitrary waveforms.

2. *To develop a metrological infrastructure for calibration of high voltage (3 kV) and high current (1000 A) DC transducers and measurement systems under dynamic conditions with typical timescales from a few hundreds of milliseconds to a few seconds.*

Present calibration measurement capabilities (CMCs) for AC power declared by NMIs only deal with static, pure sinusoidal waveforms in the frequency range from 40 Hz to 100 kHz for voltage and a current amplitude of hundreds of volts and tens of amperes. No CMCs for DC power are currently declared in the BIPM database (KCDB).

In order to guarantee accurate on-site losses and efficiency measurements, this project will develop new and improved traceability for DC dynamic signals (voltage and current ramps) with slew rates from 500 A/s to

10 kA/s and from 100 V/s to 10 kV/s with amplitudes up to 1200 A and voltage 3 kV. The overall target uncertainty will be 0.01 %. Moreover, the project will upgrade the systems developed in the previous EMPIR project 16ENG04 MyRailS by providing traceable systems for AC and DC distorted power measurement even under dynamic conditions, up to 20 kV 300 A AC and 4 kV 3600 A DC. These systems will emulate the relevant load fluctuation experienced in the transportation systems. So far, the project has undertaken preliminary experiments for generating dynamic current signals with constant slew rate that involves high-current inductors used in Magnetic Resonance Imaging (MRI).

3. *To develop, calibrate and apply on-site setups and algorithms for the measurement of the energy losses of non-conventional AC/DC substations and the charge-discharge efficiency of electric storage systems with an overall on-site target uncertainty of 10 % of losses. The setups allow capturing signals from DC to 20 kHz to perform Power Quality and transient event analysis.*

System efficiency is currently demonstrated by manufacturers using simulations only, and without a standardised approach for the validation of the simulator in terms of reliability and accuracy. Even the standard EN 50641, released in 2020, lacks full coverage of measurement of all quantities necessary for a complete determination of system energy efficiency.

This project will develop and test a hybrid tool combining a power-flow model of the transportation system with distributed measurements performed both at substations and on-board trains. The hybrid tool will provide the energy saving introduced by non-conventional substations together with an associated uncertainty and a sensitivity estimate, as well as an estimate of how well correlated the voltage control at substations is compared to on-board trains. Information on the optimum number and position of measuring points will also be provided with the associated uncertainty. So far, the project has developed and implemented a new calibration facility named ALFO to calibrate current measuring systems for DC signals with superimposed AC ripple, in the range 100 Hz – 20 kHz. The system can generate DC signals up to 2 kA with AC amplitude signals up to 20 A and to determine the complex ratio of the current sensor or of the AC ripple measuring system. This setup will be used in the characterisation of the Energy Efficiency Measurement system that will be used on site for the efficiency determination of the AC/DC power converters.

4. *To develop, characterise and determine the accuracy of a hybrid method based on the combination of field measurements and models for the determination of the energy saving provided by the upgraded DC supply system in real operating conditions.*

The current state of the art for the determination of the impact of non-conventional substations in terms of energy saved is based only on simulations, which are typically built upon rated quantities (e.g. supply voltage) and defined operating conditions which can vary from actual values. The project will go beyond this by developing, characterising and determining the accuracy of a hybrid method based on the combination of field measurements and models (simulations). The hybrid method will be used for the determination of the energy saving provided by the upgraded DC supply system in real operating conditions.

So far, the project has designed the measurement setup which will be applied to line 10B of Metro de Madrid. 5 Substation are planned to be monitored in terms of voltage and current. Electrical quantities on onboard trains will be also monitored thanks to the on-board control system.

Outcomes and impact

The project will positively influence the assessment of the energy efficiency of DC railway systems, in particular those with new bi-directional substations. Thus, providing much needed knowledge to power transformer and converter manufacturers, substation designers and installation engineers. The new instrumentation developed in the project will also allow for the first time unique on-site determination of energy efficiency (at the MW level) of power transformers and of AC/DC and DC/DC high-power converters under real operating conditions. Furthermore, the project will provide a methodology for accurate determination of energy saving introduced by non-conventional substations.

Outcomes for industrial and other user communities

The new facilities for on-site AC and DC power measurement will allow the first-ever determination of losses of high-power high-efficiency (> 97 %) converters under actual grid conditions and for dynamic load conditions. This will provide unique insight to the DC transport industry regarding the actual efficiency of railway supply systems in the presence of grid harmonics and other disturbances. Furthermore, a reliable and traceable measurement system for the determination of harmonics/ripple on AC and DC supply systems will support the verification of the electric pollution introduced by the power converters for the different operating conditions. The experience gathered by the on-site measurements (within the project) will be used to create a Best Practice Guide that can be used to simplify (and thus reduce cost thereof) on-site compliance assessment activities to the technical requirements of railway transportation systems tenders.

The project will also develop and make available a hybrid method, combining measurements together with power-flow models. This hybrid model will allow end users to determine the energy saving provided by the installation of non-conventional substation(s) in DC railway systems.

A clear and accepted definition of parameters which quantify the efficiency improvement is of vital for the trade exchange between the manufacturer (or contractor) and infrastructure owner (or operator). An example is line receptivity, a parameter that is more and more present in tender technical requirements. The project will provide a clear definition and methodology to estimate receptivity in different operating conditions using the project's hybrid model. This will prevent disputes between customers and providers of new DC railway supply systems.

Metrological and methodological tools will be produced by the project for definition of and measurement of the conditions for the optimised coordination of the reversible substation and storage system. This will support the compensation of deviations from the ideal power exchange among running trains in braking and traction conditions and will allow the removal of the dissipative rheostatic braking system from on-board trains. Ultimately, this should provide major savings to operators of DC railway systems.

To facilitate the uptake of project's outputs there will be stakeholder engagement with industrial stakeholders including railway, metro, tramway infrastructure managers, railway operators, power converter manufacturers, installation engineers, railway supply system designers. The participation of industrial participants in the project and the establishment of a Stakeholder Committee will help to ensure that the project outcomes are carefully aligned with industrial needs. The project's Stakeholder Committee has been set-up and has 14 members which include ADIF, INFRA.TO, EMH, ITALCERTIFER, IEC TC9 MT62888, HaslerRail, MONT-ELE, PTFE, RATP, Railenium, RENFE operadora, Schneider electric, Supergrid Institute, UITP.

Outcomes for the metrology and scientific communities

The project's laboratory facilities and procedures developed for the characterisation of DC and AC broadband voltage/current sensors and power measurement systems used for on-site measurements will be the basis for the submission of new CMCs under actual grid conditions (i.e., with ripple and harmonics).

The new metrology knowledge gained by the project, in the development of the new laboratory facilities and in its subsequent use for calibration and verification of the voltage/current sensors and the power measurement systems will be an important metrology outcome. This knowledge will be shared with the metrology community via communication and dissemination to the EURAMET Technical Committee for Electricity and Magnetism (TC-EM) and in particular Sub Committee (SC) Power and Energy, the EMN on Smart Electricity Grids. It is expected that the new facilities for calibration of DC voltage and current sensors in the presence of ripple, as well as the new Energy Efficiency Measurement Systems (EEMSs) for on-site efficiency measurements in transport systems will raise significant interest in the metrology community.

The project's measurement campaigns will provide unique data on DC railway systems, with accurate uncertainty characterisation, that will be very useful for further research into the statistical analysis of power flows, as well as for designers, who will, for the first time, have access to data that represents the real energy state of the system with information on its variability. The methodology can also be applied to different contexts (such as DC grids and micro-grids, power converter design) and used to develop designs more tailored to them. Furthermore, the measurement campaigns will provide unique insight into the efficiency of power transformers and converters under actual grid conditions and varying load conditions. At present, there is hardly any scientific literature on this subject due to the complexity of the required measurements.

So far, the project has been presented and disseminated its results to stakeholders via 2 conferences, the 2023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS), in Switzerland, and the International Workshop ICT for RAILWAYS in Munich.

Outcomes for relevant standards

The project's outcomes will contribute to the research priority declared by the IEC TC9 and CENELEC TC9X on the efficiency determination of power converters installed in railway DC substations and on the accurate determination of the energy saving introduced by non-conventional substations. Indeed, the project has already provided input to IEC TC9 Electrical equipment and systems for railways, CENELEC TC9X Electrical and electronic applications for railways and CEI CT9 (the Italian mirror committee for IEC TC9). In particular, the project will provide input to IEC TC9 WG50 and project team (PT)63477 that specifically deals with reversible substations, CENELEC subcommittee 9XC WG11 on the measurement system and on the procedures for losses and harmonic/ripple determination.

The project addresses the need expressed by CENELEC TC14 for research on accurate on-site determination of power transformer and power converter losses under actual distorted conditions. The results of the on-site campaigns in the project and the developed methodology will be promoted within CENELEC TC14 and IEC TC11, to enable possible uptake of project results in a new technical specification. Further to this, the project will provide input to IEC TC9 Maintenance Team (MT)62888 CENELEC T9 WG37 and CENELEC/IEC TC38.

Longer-term economic, social and environmental impacts

The project's new measurement infrastructure for the traceable quantification of efficiency will provide much needed information on substations under actual operating conditions and will in the long-term foster the dissemination of new energy-efficient technologies for power conversion in DC railway systems. A reliable methodology to quantify the cost-benefit ratio of new investment devoted to energy saving will also positively contribute to decision-making processes on the uptake of these investments. The increase of the braking energy recovered by the system should also have a positive contribution to the longer-term European policy for a smart and sustainable European transport system as well as benefitting climate and environment policies by helping to support CO₂ savings.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2023, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRIM, Italy	6. MM, Spain	
2. FFII, Spain	7. SUN, Italy	
3. LNE, France	8. Systra, France	
4. VSL, Netherlands	9. UNIGE, Italy	
5. VTT, Finland	10. UTwente, Netherlands	

Publishable Summary for 22NRM05 MeLiDos

Metrology for wearable light loggers and optical radiation dosimeters

Overview

New standardised metrics for measuring the physiological, non-visual effects of light have been recently introduced in CIE S 026 and wearable light loggers (also known as light dosimeters) have emerged as a way to measure a person's light dose. However, the optical characterisation of these dosimeters remains challenging because of the compromises needed to make them wearable and affordable. This project aims to provide the scientific and industrial communities with the necessary tools (e.g. best practice guides) for the characterisation and use of wearable light loggers.

Need

Daylight affects human physiological activity and regulates many aspects of society (e.g. waking hours, alertness). On the other hand, the invention of electric lighting has led people to spending more time indoors during the day, including working remotely from home, and staying up later in the evening. However, the intensity of artificial light is only a fraction of that of daylight (a half for a cloudy sky, and less than 1 % of a sunny afternoon), while their spectral compositions differ in terms of blue light proportion. This point is of particular importance because of melanopsin, a photo-pigment present in the eye and involved in physiological responses to light but not in direct vision, called Non Image-Forming (NIF) effects. Implications for health and well-being vary from mood and wakefulness to sleep deprivation, including even more severe health problems, such as heart diseases and cancer. While the study of lighting sources can be performed in laboratories under controlled conditions, the light humans receive under actual environmental conditions is very different due to e.g. window placement, reflectance of materials in the surrounding, habits, etc.

Wearable light loggers are currently being used for the measurement of light exposure on humans, as they are wearable and provide light exposure data during the course of a whole day. These light dosimetry time series are then correlated to other factors, such as melatonin levels or heart rate, to investigate the physiological effects. Although they are compact and lightweight, they often have a black-box design where the sensor technology (e.g. filter-based or spectrally resolved), the data processing (e.g. sampling rate, averaging or other data processing, etc.), or both, are unknown, which makes evaluating their performances even harder. It can then lead to inaccuracies, inappropriate metrics or conclusions due to misinterpretation or incomplete data. There are currently no guidelines or standards for the characterisation of light loggers, and the collected data are thus often considered unreliable due to inaccurate device specifications and/or data processing or interpretation (e.g. a user not familiar with the field misinterprets a specification or metric).

In TN002:2014, CIE has identified the need for the photobiological and photometric quantities to be harmonised. With the rapidly evolving field of lighting (future revision of CIE S 025, publication of CIE S 026, introduction of daylighting by EN 17037 and revision of workplace lighting in EN12464-1) and the spread of wearable devices of all kinds, it is important to keep metrology recommendations and guidelines up to date to ensure reliable studies well support health recommendations and policies.

Objectives

The overall aim of the project is to introduce metrology for light dosimeters, and in particular for light loggers designed to respond to the needs raised by CIE S 026 for measuring melanopsin-related metrics. More specifically, this project will deliver the metrics and procedures, as well as guidelines based on use cases, in order to lay the groundwork addressing the normative standards' needs.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: March 2024

The specific objectives are:

1. To develop and validate new characterisation methods, and define a validated set of quality indices for wearable optical radiation dosimeters, with a focus on ranges relevant to daily life (i.e. UV and visible). Their validation will be performed against lab-based instrumentation for parameters (e.g. wavelength sensitivity, linearity and angular response) in an intercomparison exercise. The quality indices will be based on those defined by ISO and CIE for illuminance meters and luminance meters.
2. To develop data analysis methods to verify and increase the quality of data, as well as to establish the correlation between different datasets to improve reproducibility and make comparisons from different devices more reliable.
3. To analyse use cases for wearable light loggers based on end user needs, and to then produce recommendations based on those needs on i) (meta-)data model and data formats, as well as summary metrics and on ii) the practical use of light loggers, including device placement, compliance and quality control.
4. To evaluate the performance of new portable devices able to measure spatially resolved photobiological quantities and to compare them with spatially averaging devices, to determine relevancy depending on use case. Additionally, to investigate the shortcomings of current devices regarding their use and to investigate the benefits and drawbacks of spatially-resolved devices.
5. To collaborate with CIE Division 2 and Division 6, and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs, including the provision of recommendations in a form that can be incorporated into future standards at the earliest opportunity. Additionally, to promote the results to other relevant parties such as lighting experts, chronobiologists and sleep specialists through various communication channels available to the participants.

Progress beyond the state of the art and results

Development of characterisation methods and quality indices for light loggers and optical/UV radiation dosimeters (Objective 1):

Though it has been known for over two decades that light has a profound effect on human health and wellbeing, only recently has CIE S 026 defined spectral sensitivity functions, quantities, and metrics to quantify the light triggering these effects. The spectral measurement and characterisation of light sources in testing laboratories are usually well understood and the measurement uncertainties are at an acceptable level for current uses. In recent years, various wearable light loggers and UV radiation dosimeters have been developed to enable the measurement of spectrally weighted irradiances and irradiance doses in field experiments, implementing the standard CIE S 026. Since these instruments need to be portable and light weight, their design differs from those typically used in laboratory environments. Moreover, since these instruments are to be used in field experiments and deployed in numbers, the evaluation of their performance needs to be cheap and time-efficient. Traditional methods of providing traceability for example by measuring the spectral responsivity with the narrow band source are thus not suitable. So far, no standardised methods exist to characterise wearable light loggers and UV radiation dosimeters.

This project will build a metrological framework for the characterisation of wearable light loggers, giving methods for their evaluation, validation, and traceability. The developed methods will be validated through an intercomparison, contributing to measurement capabilities at NMIs as well as in industry. Performance indicators, consisting of a set of quality indices, will be developed in order to make it easier for users to assess the performance of a device in terms of e.g. linearity. The project outcomes will be summarised in a publicly available good practice guide (GPG), which will support CIE in the development of standards for the characterisation of wearable light loggers. The overall goal is to provide guidance and methods to stakeholders on how to reliably characterise wearable light loggers.

In collaboration with CIE JTC 20, the project identified 64 different devices used in studies on the physiological effects of visible light, with a wide diversity in technology, wearing position, and with often limited availability. The project identified several devices of interest for characterisation, limiting its choice to devices that allegedly reported metrics related to non-image forming effects. The project's participants are in the midst of acquiring several of these devices for characterisation.

The project also identified 20 devices to measure UV exposure, most of which are discontinued. The core sensor for these solar UV dosimeters is often discontinued too, and characterisation for UV sensors is more

tricky. Coupled with less demand due to chemical patch alternatives, solar UV dosimeters are less available on the market. As such, the project will only be able to evaluate 2 models of solar UV dosimeters, and plans to potentially also include a hand-held version of such a device.

Development of data analysis methods for data quality verification and data reproducibility (Objective 2):

The data currently collected by wearable light loggers, are usually affected by multiple factors, for example who is wearing them (i.e. if the device is worn correctly, or at all times, etc.), the indoor/outdoor environment, etc. It is therefore necessary to include processes and data analysis methods to validate the data. This project will provide the necessary guidelines for preparing and carrying out field studies with wearable light loggers in a way that promotes data quality and reliability, with a user-oriented mind-set. This will include data and metadata formats and data validation tools and recommendations to facilitate the reproducibility, data transfer and comparison between data sets. A research-oriented software ecosystem will be included, comprised of various modules for data format conversion, data analysis, validation, and visualisation, as well as a cross-comparison between different devices and studies with harmonised data format.

A software ecosystem is being developed by the project to provide research user with a powerful tool to analyse, validate and visualise their data and results and make them FAIR. The software goes by the name LightLogR and is currently already functional (documentation: <https://tscnlab.github.io/LightLogR/>, code: <https://github.com/tscnlab/LightLogR>). More features will be added during the project, in particular concerning data and metadata formats and validation. The project's participants are in contact with several device manufacturers and users to get feedback and ideas on this particular aspect.

The project also collected useful information by interviewing experts who used light loggers in the field. This information will be used to design a set of auxiliary data which will help during the validation and consolidation of the light logging data, granting more confidence in the subsequent analysis.

Meta-data recommendations were put forward by a working group within the Daylight Academy, a stakeholder of the project, in a paper in late 2023 (under review). These recommendations will be further developed and validated through the project.

To analyse use cases for wearable light loggers based on end user needs, and to then produce recommendations based on those needs on i) (meta-)data model and data formats, as well as summary metrics and on ii) the practical use of light logger (Objective 3):

There are multiple applications for wearable light loggers and different devices designed to answer specific applications. For example, a study on the effect of light sensitivity on ASD (Autistic Syndrom Disorder) patients will have different requirements to a study of wall paint colour on wakefulness of office workers, both in terms of device technical specifications and in terms of practical use (e.g. when, how the device is worn, data relevancy, etc.). There are currently no guidelines or recommendations related to the proper selection and use of wearable light loggers. This project will define a usage landscape based on the applications' needs and provide recommendations on the quality indices and other characteristics that a user should pay attention to while choosing and using wearable light loggers.

A survey was carried out with more than 20 experts in the field of chronobiology, health and well-being, in order to understand their experience of light dosimetry, including the purpose of their studies, their use of light loggers, the limitations and problems encountered both on the wearer and scientist side, and several other key information. A summary of the user needs based on these interviews is currently being drafted.

The experience of the scientists with the data was also a key part of the survey. Things such as how the data was validated and analysed, and the confidence the users had in the data was investigated. A draft protocol was designed, incorporating these findings for a field-testing demonstration to be carried out later.

Portable devices performance evaluation for the measurement of spatially resolved photobiological quantities. Comparison with spatially averaging devices and investigation of benefits/drawbacks of spatially-resolved devices (Objective 4):

The fast development of wearable devices and the spread of their use for aggregating data with constellations of devices or for behavioural studies, poses a major challenge for the reliability and traceability of the data generated by these devices. New sensor technologies for wearable light loggers will be investigated in this project in order to ensure the delivered methods and recommendations will remain transferrable to new technologies. In particular, the use of spatially resolved devices will be investigated since the eye is also a

spatially resolved sensor and the study of non-visual effects of light should not stop at spatially averaged light levels.

Several sensors were identified with a potential for their incorporation into a spatially-resolved light logger (2D light logger). Most of the devices came in the form of micro-cameras used in various applications such as medical diagnosis, augmented reality, or even sensors from smartphones. The availability and practicality of some of the sensors for custom applications such as this research is questionable, and the project has yet to acquire relevant sensors to start testing the viability of using them in 2D light loggers.

CIE JTC 20 expressed the need for such devices during the CIE quadrennial conference in Ljubljana, in September 2023, with several groups of researchers casting doubt on the relevance of illuminance as a reliable metric for non-visual effects, since the eye does not behave like a cosine-corrected illuminance meter, but like an imaging apparatus. Some research also showed evidence of spatial dependence of non-visual effects of light, with considerations such as pupil size, eyelid position, or even the spatial repartition of the melanopsin-containing cells in the retina.

An investigation into the benefits and drawbacks of 2D light dosimetry was carried out by the project's participants, based on which a questionnaire was prepared and distributed to experts in the field of light dosimetry for their feedback. There are currently around 10 replies, with varying degrees of expertise on the technical aspects of light dosimetry, which points to a need of also raising awareness on the incompleteness of data from spatially-averaging light dosimeters.

Outcomes and impact

The project has so far participated in various international instances of standardisation committees, notably chairing the CIE JTC 20 on 'Wearable alpha-opic dosimetry and light logging methods, limitations, device calibration and data schemes'. At the CIE quadrennial conference in Ljubljana, September 2023, several participants were present and shared the news about the project, its goals, and interacted with potential stakeholders. Several presentations of the project's goals, methods, participants and early results were given, mainly on the national level. Introductory trainings on the use of the software ecosystem were given online to interested parties among stakeholders and the participants' network. A workshop was also organised on light beyond vision. The identity framework of the project was set, with the creation of the website, flyers for events, poster and presentation templates, and the first newsletter was distributed to the stakeholders. All materials from the newsletter to the stakeholder workshop presentations were made available on Zenodo and/or on the project website. Introductions to the subject were made to the general public through the University of San Pablo's science week (for students) and through an article in the general Spanish press.

Outcomes for industrial and other user communities

The project will provide the industrial and scientific communities in the field of wearable light loggers and UV radiation dosimeters with the methods, recommendations, and guidelines as necessary for the characterisation of these devices. The quality indices will not only benefit users as a way to assess the performance of a device but also industry that wants to design improved devices or similar devices that look at other wavelengths.

Improving light dosimetry will also enhance the quality of studies regarding Non-Image Forming (NIF) effects of light and benefit lighting experts, interior architects and similar professions by providing them with useful tools to evaluate their work in situ. As both regulations and public awareness are progressing towards more health considerations in buildings, it will provide opportunities for the lighting industry to improve their products to be more in line with trustful, state of the art research. Light loggers could also be used by these experts, empowering them with new tools to easily monitor the lighting changes throughout a day or with changes in furniture, paint, and other interior arrangements.

Currently, manufacturers have expressed a lot of interest in the characterisation methods for their devices as well as in the data and metadata framework to be developed in the project.

Outcomes for the metrology and scientific communities

The project will deliver recommendations and guidelines for the characterisation and use of wearable light loggers. This will improve the quality and reliability of the data generated by clinical studies, as well as the robustness of their results and conclusions. Researchers and clinical staff will be able to choose devices which best fit their application as well as get more reliable light dosimetry data and therefore, more reliable conclusions in their studies.

Several researchers have developed their own devices because they found commercially available devices unsatisfactory for their needs. They expressed interest in the characterisation methods and proposed a collaboration to include their devices in the development of the methods or the comparison that will follow. Several research scientists were also impressed by the LightLogR software ecosystem, expressing their willingness to either contribute data to further develop the software, or to use it on their own. While work on solar UV radiation dosimeters will not be as extensive in this project, it will still benefit scientists by providing them with more reliable tools to measure UV doses in the field and assess its impacts on human health. Currently, UV doses are generally measured with chemical patches, which are both cheaper, more available on the market, but also provide less reliable, quantitative results. One of the two main issues for UV dosimeters is the fact that the devices are often discontinued, so finding relevant, available devices is a challenge that the project but also the beneficiaries of the project's work will face. This is due to the manufacturers having the same issue with the core sensors in these devices, which are often discontinued. The second main issue is about the difficulty in characterising the device, which is being addressed by the project.

The project will also improve the performance of the wearable light loggers that will be designed for and used by the general public, providing more exhaustive and accurate information about the light dose they receive. Data provided by the general public (in this case light dosimetry data) can be used for Big Data studies. Making this light dosimetry Big Data reliable is again key for the researchers that will use it to make statistical analyses of practices in the general public.

The metrology benefits are more straightforward, as the project will lay the groundwork for normalisation bodies regarding wearable light loggers, with the methods not only limited to wearable light loggers for NIF effects of light, but also including UV radiation dosimeters.

Outcomes for relevant standards

The results of this project will be used to complement CIE S 026, which defines the metrics for NIF effects of light, with recommendations on how these should be properly measured, such as device requirements, characterisation and practical use. The project will also contribute to the implementation of standards in daylighting EN 17037 and workplace lighting in EN12464-1 by improving the reliability of the tools available for building experts to assess their compliance to those standards. As currently there is no European standard on solar UV exposure for outdoor workers, this project should contribute to the development of new standards on solar UV exposure, in particular by providing insights for potential Personal Prevention Equipment (PPE) against solar UV radiation.

The project is working in tandem with CIE JTC 20, with the project being focused more on applications rather than guidelines, providing validated and practical methods for characterising light dosimeters and actually using them in the field. It also expands to solar UV dosimeters and spatially-resolved devices. This collaboration includes cross-checking the state of the art for wearable light loggers and sharing insights into current practices on the characterisations of illuminance meters, the devices most closely related to current technologies of wearable light loggers, which the project's participants are more familiar with.

Longer-term economic, social and environmental impacts

Currently, very little is known about how light exposure affects human health and wellbeing. The introduction of metrology for wearable light loggers will ensure scientists and clinical staff have reliable data to better understand the role of lighting in human health and wellbeing. Chronobiologists and sleep specialists will benefit from having reliable tools to study and understand the effect of light exposure on human physiology. The confidence in scientific results mentioned above will hasten the emergence of efficient guidelines and standards for the lighting field as well as health experts. This in turn will improve the livelihood, wellbeing and productivity of the European and other communities for the long term. The same health benefits are expected for the extended work to UV radiation dosimeters. The emerging increase in UV exposure as a result of global warming is expected to increase the number of skin cancer case, as warmer and sunnier days means more time spent exposed to UV radiation. In view of this, characterisation methods and quality indices for the performance of solar UV dosimeters with the aim of optimising protective measures and effective strategies for skin cancer prevention are of great importance.

Moreover, connected devices for monitoring various parameters are already available to the general public (Internet of Things or IoT) but it is not always known what the data means exactly, both among the general public and sometimes, the manufacturer. Recommendations and future standards for the characterisation of

light dosimeters, as well as recommendations for the formatting and use of the data, will improve the understanding of the health implications of light exposure by manufacturers, and in turn by the end user.

Potential future uses and follow-up work

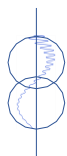
The characterisation methods developed in this project are applicable in a wider frame to other portable light logging devices. This includes devices for monitoring plant growth and health in agriculture for example. The LightLogR framework developed in the project is already being used to compare datasets and validate measurements. The emphasis the participants put on practicality, exhaustivity and methodology will make it easier to both adopt the methods developed, which will enhance reproducibility and comparability for future results. The importance of getting spatially-resolved data is also highlighted by many experts in the field as the eye is an imaging apparatus, and the topic was prominent at the CIE quadrennial conference in Ljubljana for light dosimetry in various situations. The project will keep its contribution closely related to currently used devices in order to keep the consistency that constitutes the core of its effort.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months	
Coordinator: Fabien Eloi, LNE		Tel: +33130691340	
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Chief Stakeholder Organisation: Commission Internationale de l'Eclairage (CIE)		Chief Stakeholder Contact: Diana Wernisch, CIE General Secretary	
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:	
1. LNE, France	7. FUSP-CEU, Spain	13. BAuA, Germany	
2. Aalto, Finland	8. Iberoptics, Spain		
3. CMI, Czechia	9. INEGI, Portugal		
4. RISE, Sweden	10. THUAS, Netherlands		
5. TUBITAK, Türkiye	11. TUM, Germany		
6. VSL, Netherlands	12. UCM, Spain		
Associated Partners:			
14. HSLU, Switzerland			
15. METAS, Switzerland			
16. SFI Davos, Switzerland			



Publishable Summary for 22NRM06 ADMIT

Characterisation of AC and DC MV instrument transformers in extended frequency range up to 150 kHz

Overview

This project will address the standardisation needs of IEC TC 38. It will develop traceable measurement methods and procedures for the characterisation of Instrument Transformers (IT) used to measure disturbances up to 150 kHz in Medium Voltage (MV) grid. The project participants will closely interact with IEC TC 38 to ensure the incorporation of the project outputs for the revision or new written standards. The metrology community, manufacturers of MV systems and academia will also strongly benefit from the project results.

Need

Society's increasing use of switching devices (inverters, bulky power electronic converters, active filters, etc.), both as loads and as part of generators, especially for renewable energy sources, has driven the consequent proliferation of conducted disturbances on grid voltage and current, also at MV level, up to hundreds of kilohertz, due to the harmonics of the components around the switching frequency. Consequently, standardised methodologies, procedures and infrastructures for calibration, characterisation and testing ITs beyond frequencies covered by currently available infrastructures are needed. Characterisation of ITs used for MV HFM in AC and DC MV grids is one of the three priority topics submitted by CEN/CENELEC for this call.

Suitable parameters to define the accuracy and the performance requirements of ITs up to 150 kHz are not available, and there is an urgent need to standardise procedures to test ITs up to this range of frequency. Indeed, the standards which are currently in force include requirements only up to 20 kHz and test procedures only for 50/60 Hz. New calibration methods for AC and DC ITs, with high accuracy class, at frequencies up to 150 kHz are needed. High voltage and high current metrological infrastructures, capable of ensuring the traceability for this extended range of frequency are also missing.

The development of setups to generate realistic test voltages (AC or DC up to 36 kV) and test currents (AC or DC up to 2 kA) will promote new calibration services for the electrical industry and deposit new calibration services for NMIs. Indeed, the achievements of NMIs during previous or ongoing European projects and the present available capabilities and facilities, among all the actors combined, do not cover this topic since frequencies higher than 20 kHz and up to 150 kHz represent new issues for the AC electrical networks.

Objectives

The overall objective of the project is to develop traceable measurements and characterisation methods of instrument transformers used for high frequency measurements in AC and DC medium voltage grids.

The specific objectives of the project are:

1. To identify performance requirements both for Instrument Transformers as well as for the measuring instruments connected to them, based on disturbances in AC and DC MV grids (system voltage < 36 kV) and on future measurement needs in the frequency range up to 150 kHz.
2. To establish suitable parameters for the definition of the accuracy of voltage and current transformers in the frequency range up to 150 kHz. To define suitable calibration conditions and procedures for the accuracy evaluation.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: July 2024

3. To facilitate the laboratory set up to generate test voltages (AC or DC at <36 kV system voltage) and test currents (AC or DC at <2 kA). Preference will be for generation of the power frequency quantity with superimposed components with frequencies up to 150 kHz, but at a fraction of the magnitude of the power frequency components.
4. To develop reference measuring systems for the calibration of Instrument Transformers in the frequency range up to 150 kHz at voltage level up to 36 kV system voltage and current levels up to 2 kA and to develop traceable calibration chains for these new systems.
5. To contribute to a revision of written standards by providing the data, methods, guidelines and recommendations, which are necessary for the accuracy verification of Instrument Transformers used up to 150 kHz, to IEC TC 38 Instrument Transformers. Outputs should be in a form that can be incorporated into standards (IEC 61869 standard family) at the earliest opportunity and communicated through a variety of media to the standards community and to end users (Transmission System Operators, Distribution System Operators, customers). In addition, to interact with the European Metrology Network on Smart Electricity Grids.

Progress beyond the state of the art and results

Reference measuring systems, traceable test procedures and validated reference setups – objectives 1, 2, 4

Voltage and current traceability for AC and DC ITs in the extended range of frequency up to 150 kHz do not exist yet. High Voltage and high current measuring instruments with large bandwidths exist, but they have never been validated for such applications, which require high accuracy to assess ITs of 0.1 % class or better. These are usually adopted to measure only the fundamental component (AC 50/60 Hz or DC) or to acquire impulses such as lightning or switching impulses. So, the first thing to be done is the identification of the performance requirements for ITs as well as to measure instruments connected to them (objective 1). A statement of uncertainty limits, for accurate IT characterisation, along with the definition of suitable parameters and procedures, must be developed to measure instruments, available at NMIs or on the market (objective 2). Other high voltages and high current accurate measuring systems need to be developed by considering the specificities of grid disturbances and test circuits (objective 4).

Generation techniques of realistic AC and DC voltage and current waveforms – objectives 1, 3

The facilities at NMIs and testing laboratories that generate AC/DC current and AC/DC voltage with superimposed components up to 150 kHz are limited. Typically, the best NMI facilities of AC/DC voltage generation for the level of 36 kV do not go beyond 10 kHz. For current generation, the best NMI facilities at 2 kA do not go beyond 9 kHz. Similar results are noticeable on the market, where manufacturers of high voltage and high current sources propose systems that perform less than those at NMIs. Validated and stable generators remain an important tool, which is considered an essential part of the test circuit. Realistic AC and DC voltage and current waveforms, with spectral content up to 150 kHz, must be identified for the characterisation of ITs (objective 1).

A preliminary setup, constituted by two series-connected voltage generators able to generate voltage waveforms composed by an AC fundamental tone (50 Hz – 60 Hz up to 3.6 kV) and high-frequency tones (9 kHz to 150 kHz up to 50 V) has been arranged and characterised. An archetype of reference voltage sensor (up to 4 kV, 9 kHz to 150 kHz) has been arranged and characterised. This activity has been described in a conference paper and in a paper submitted to IEEE Instrumentation and Measurement.

Enhance the achievements of previous and ongoing European projects – objectives 1, 2, 3, 4

Several previous or ongoing projects dealt or are dealing with measurements of high voltage or high current with superimposed components up to several kilohertz (e.g., ENG04 Smart grid, ENG52 Smart Grid II, 16ENG04 MyrailS, 17IND06 Future Grid II, 18NRM05 SupraEMI, 19NRM05 IT4PQ, 20NRM03 DC grids). To the best of the participants' knowledge, no NMI has the capability for simultaneous generation of power frequency (DC or AC 50/60 Hz) currents at 2 kA, or voltages at 36 kV, with high superimposed frequency components up to 150 kHz, and in the literature this problem has not yet been solved (objectives 1, 3). The work in this project will enhance the achievements of previous and ongoing European research projects in the field of MV grid measurements (objectives 2, 4). New facilities and capabilities could be duplicated and implemented by all NMIs and testing laboratories. The objective is to grant every actor the possibility to

calibrate AC and DC ITs, of 0.1 % class, up to 150 kHz and for voltage up to 36 kV and current up to 2 kA (objectives 1, 2, 3, 4).

Outcomes and impact

One of the first steps was the creation of a stakeholder committee with 14 members and including representation from 6 different countries. Comments and advice have been collected and inclusion into the project direction. A project webpage has been developed and set up at <https://admit-project.eu/>. Furthermore, the project aims and some results have been presented at two international scientific conferences. The first Stakeholder workshop was held in June 2023 at INRIM, Turin, Italy.

Outcomes for industrial and other user communities

The project will have at least 14 stakeholders ranging from Instrument Transformer manufacturers, TSOs and DSOs, measuring instruments manufacturers, HV/MV equipment manufacturers, and standard development organisations. These organisations will benefit from the project outputs, which will boost the development of a strong return advantage for both AC and DC MV grids. The project will improve high-frequency measurements in distribution systems which are highly important for regulators and utilities in all European countries. The project's outputs will support the provision of a stable, secure, and efficient energy supply even if connecting multiple energy sources. The realisation of the necessary metrological infrastructures will represent a benefit for all the actors involved in MV grids.

The European power industry has a leading position in producing and testing ITs with significant experience in both AC and DC types and voltage and current IT types. The traceability developed in this project will allow for a full assessment, reducing unnecessary safety margins and thereby increasing the operability of manufactured systems. For example, the industry will benefit from traceability methods, characterisation methods, testing set-up and generating circuits to assess them as early as possible their systems.

Manufacturers of ITs are under pressure, as new development is expected to produce accurate apparatus capable of operating in MV grids at high frequencies. They will benefit directly from the metrological work of the project, for example by exploiting the procedures for characterisation, the possible development of accurate standards, the uncertainty calculation, and the list of the identified influencing quantities.

Outcomes for the metrology and scientific communities

Metrology and scientific communities will benefit from new measurement capabilities in an area where although much has been achieved to date, in particular from previous European research projects, the limits were never pushed so far.

The scientific and technical objectives addressed in this project will be a major step forward in the metrology community by providing several important additions and extensions to NMI/DI Calibration and Measurement Capabilities (CMCs) related to the calibration of DC voltage, AC voltage, DC current, AC current and up to 150 kHz.

NMIs will improve their knowledge and will be able to perform new traceable measurements on ITs and offer new calibration services. This project will improve the metrology for high voltage and other related quantities through new techniques for applying precision measurements and develops competencies in a multidisciplinary approach. The objectives will allow a larger number of test laboratories to benefit from research projects in the field of high-voltage/instrument transformer metrology. This will lead to a significant improvement in the overall European metrology capacity

Outcomes for relevant standards

The whole project has been structured to answer specific objectives expressed directly to EURAMET by IEC TC38, Instrument Transformers through the CEN STAIR EMPIR Platform, and will have significant impact on TC38 and working groups through new characterisation methods.

The project will generate results that will answer to TC38-specific objectives but also they will be very valuable to other standardisation committees such as TC8-SC8A, Grid Integration of Renewable Energy Generation, TC13, Electrical energy measurement and control, TC17, High-voltage switchgear and control gear, TC22-SC22F, Power electronics for electrical transmission and distribution system", TC77, Electromagnetic compatibility, TC85, Measuring equipment for electrical and electromagnetic quantities, TC95, Measuring relays and protection equipment and TC 51, Magnetic components, ferrite and magnetic powder materials.

Longer-term economic, social and environmental impacts

The project aims to support improvements to grid stability and operability, to ensure a sustainable and affordable energy supply for European society. Indeed, high-frequency measurements are important due to the proliferation of new-generation switching power converters which are connected directly to AC and DC MV grids, and whose emissions may interfere with vital grid operations. The primary aim of the project is to ensure that all the ITs connected to MV grids could operate in a stable and safe way with the presence of high-frequency components. With the research and outputs from this project, high-quality testing facilities will give strong support for European manufacturers to remain leaders in grid innovation. This has a direct impact on the competitiveness of the European power industry in the international market.

Many more instrument transformers are needed to reliably meet the increasing demand for renewable electricity around Europe and the world. The installed global stock is expected to increase by a compounded annual growth rate of 3.7 % more than doubling the number of instrument transformers until 2040. An IT's performance has a major impact on electricity use to give the non-stop operation of the equipment over its 25-year service life. Better performance translates into reduced load on the electricity system, lower electricity bills and greater reliability.

Using more efficient and accurate ITs can lead to nearly 5 % reduction of global electricity consumption. By 2040, annual electricity savings of over 750 TWh are possible saving more than 450 million tonnes of greenhouse gas emissions. With the techniques developed in this project, it would be possible to assess ITs to ensure they operate efficiently and accurately under high-frequency grid disturbance. These techniques will be available for everybody (utilities, industries, users, TCs) to take the appropriate actions to prevent undesirable events and to calculate the energy consumption precisely and saving then hundreds of terawatt hours.

List of publications

Luiso, Mario (2023) 'Characterization of Voltage Transformers for MV applications up to 150 KHZ – a preliminary study', IEEE Applied Measurements for Power Systems p. 1. Available at <https://doi.org/10.5281/zenodo.10701873>.

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2023, 36 months	
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Tel: +0039-011-3919826		E-mail: d.giordano@inrim.it	
Chief Stakeholder Organisation: IEC Technical Committee 38 Instrument transformers		Chief Stakeholder Contact: Volker Leitloff	
Internal Beneficiaries: 1. INRIM, Italy 2. FFII, Spain 3. LNE, France 4. RISE, Sweden 5. VSL, Netherlands 6. VTT, Finland	External Beneficiaries: 7. RSE, Italy 8. SUN, Italy 9. UNIBO, Italy 10. UNIGE, Italy	Unfunded Beneficiaries: 11. ARTECHE, Spain 12. UNARETI, Italy	
Associated Partner linked to VSL and SUN METAS, Switzerland			

Publishable Summary for 22NRM07 GuideRadPROS

Harmonisation, update and implementation of standards related to radiation protection dosimeters for photon radiation

Overview

Photon dosimeters are used for measuring radiation doses to protect people from the harmful effects of ionising radiation. However, the recent update of the basic standard for photon reference radiation fields in radiation protection, ISO 4037:2019, has presented significant challenges to calibration laboratories and industry, such as high costs and increased need for manpower. This project will provide protocols and guidance to calibration laboratories, metrology institutes, standardisation bodies and regulators for a harmonized approach to radiation protection measurements and calibrations. Proposals to update ISO 4037:2019 and future needs for type testing and possible implementation of new radiation protection quantities according to ICRU Report 95 will also be provided, leading to compatible procedures and requirements.

Need

Photon dosimeters are almost universally used in all radiation practices, covering personal and environmental monitoring, and emergency response, to assess the protection of people from harmful effects of ionising radiation. In the EU, the requirements for dose assessment and monitoring are set in Council Directive 2013/59/Euratom, which is implemented in national legislations. Comparable world-wide requirements are given in IAEA Safety Standard Series No. GSR Part 3: General Safety Requirements.

Radiation protection dosimeters measure ambient dose equivalent, directional dose equivalent, or personal dose equivalent. These dosimeters are tested and calibrated in photon reference fields according to the ISO 4037:2019 standard series. In the 2019 update of this standard, many changes were introduced. The new requirements result in high costs and manpower to establish such reference fields and therefore, small laboratories and emerging metrology institutes have not been able to fully implement the standard.

Furthermore, there is a need to provide guidance to implement ISO 4037 series and to provide missing data regarding ²⁴¹Am reference fields, high voltage measurements of X-ray units and the associated uncertainty estimates. In addition, harmonized procedures for traceable X-ray spectrometry are needed.

The type testing of the dosimeters is done against the IEC standards but there are many standards with conflicting requirements for the same type of dosimeter. There are also standardisation gaps, due to recent or upcoming developments in measurement technology, such as use of spectrodosimetry, new technologies related, e.g., to the use of machine learning, artificial intelligence, and other methods based on computation. Therefore, the standards must be harmonized, and future standardisation needs must be analysed.

Finally, ICRU report 95 proposed new operational quantities to replace the current quantities. This will require a revision of the type test standards and characterization study of existing dosimeters to see whether software and/or design modifications are necessary.

Objectives

The overall objective is to support standardisation in photon-based radiation protection dosimetry, related to ISO 4037 standard series, IEC standards and the changes due to new operational quantities of ICRU Report 95.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: April 2024

The specific objectives are:

1. To develop a traceable, harmonized metrological approach to X-ray spectrometry in concordance with the ISO 4037 standard series, evaluate the discrepancies between measured and calculated half value layer (HVL) of X-ray spectra and to produce data to update requirements for reference X-ray fields. To produce data for ^{241}Am reference fields and to evaluate methods to determine X-ray tube high voltage (HV).
2. To develop cost effective procedures and guidance for the calibration of dosimeters and determination of their response as a function of photon energy to enable smaller metrology institutes and other calibration laboratories to implement the ISO 4037 standard series with respect to actual quantities and ICRU Report 95 quantities. To provide training to emerging metrology institutes and to produce open e-learning materials on the calibration procedures.
3. To produce guidance on validated procedures for harmonized type testing based on IEC standards (e.g., IEC 61526, IEC 60846-1, IEC 60846-2, IEC 61017, IEC 60532, and IEC 62387) for the commonly used dosimeters with valid metrological solutions for situations where requirements in existing standards deviate and standardisation gaps exist.
4. To assess future standardisation needs and to produce a guidance document for the implementation of the new operational quantities of ICRU Report 95 into standards and regulations, and to disseminate this to policymakers, manufacturers, regulators, metrology networks, standardisation bodies and laboratories.
5. To collaborate with ISO and IEC and the users of their dosimetry standards (including the EMN on radiation protection and the IAEA) to ensure that project outputs align with their needs. To produce guidance on the implementation of new operational quantities of ICRU Report 95 into standards and regulations and recommendations. To disseminate project outcomes for inclusion into ISO 4037.

Progress beyond the state of the art and results

Harmonized approach to X-ray spectrometry and implementation of ISO 4037

Support will be given to calibration laboratories to build up their spectrometry methods by guidance documents and training on characterising the spectrometers and unfolding the measured X-ray spectra to implement the ISO 4037 standard series. Data will be produced to include ^{241}Am in the future version of the standard to harmonize this radiation field and to reduce the uncertainties in type testing and calibration of the dosimeters. In addition, information on further methods of X-ray tube high voltage determination will facilitate the implementation of such reference fields.

Training on requirements of ISO 4037 and calibration in reference fields

Hands-on training and e-learning material will be produced to support calibration laboratories to implement photon reference fields according to the ISO 4037 standard series and to apply changes due to new quantities of ICRU Report 95 in the calibration fields. The training needs and the status of applying both ISO 4037 and ICRU report 95 were identified with an online questionnaire.

Validated procedures for harmonized type testing standards

The need for harmonization of existing standards of radiation dosimeters and the need to close the existing standardisation gaps will be addressed. Analysis of the standards and overview of inconsistencies will be performed to provide recommendation for harmonization to IEC. A survey was done to assess the status of type testing practices in Europe and the type testing requirements were discussed with the stakeholder committee. A document will be prepared for manufacturers to identify relevant legal requirements for dosimeters and dose measurements in different countries.

Assess future standardisation needs and produce guidance to implement new quantities into the standards

An analysis of the state-of-the-art and upcoming technologies in dosimetry will be done. The incompatibilities of these technologies with respect to the requirements from the existing IEC standards will be evaluated and the potential needs for new or updated standards considering the new technologies will be identified and analysed. Special attention will go to the practical implementation of computational dosimetry and

spectrodosimeters to the future IEC standards. Finally, the impact of ICRU Report 95 to the ISO 4037 standard series and IEC standards will be evaluated and reported.

Outcomes and impact

The project has started to strongly engage the stakeholders within the project scope to update requirements both for setting up the laboratory calibration x-ray beams and for type testing of radiation protection dosimeters. In addition, the project and its progress has been presented in nine scientific conferences and workshops. The goals of the project have been presented to several national radiation protection authorities and regulators. Project has been introduced to technical committees of standardization bodies (IEC, ISO, DKE).

The impact of new quantities of ICRU 95 were discussed with industrial and regulatory stakeholders in a dedicated workshop. In the same workshop, type testing requirements for the future radiation dosimetry techniques were discussed and the feedback will be used to refine the contents of the technical work to establish requirements for the future type testing practices.

Within the project, technical visits have been organized among participating laboratories to discuss practical aspects of calibration beam quantification with spectrometry.

A project web page has been developed and set up at <https://lmri-met.github.io/sites-guideradpros/>.

Outcomes for industrial and other user communities

The revision of the ISO 4037 standards and the adoption of the ICRU Report 95 operational quantities have an impact on realization of radiation beam qualities and the value of the conversion coefficients from air kerma to dose equivalents, respectively. The new operational quantities introduced in ICRU Report 95, the ambient dose and personal dose, have a different energy and angle dependence with respect to the incident radiation field compared to the current quantities. Thus, these new quantities require changes in the characteristics of the measuring equipment. These changes will have consequences for all industrial stakeholders, including calibration laboratories, dosimeter manufacturers, dosimetry services and users of ionizing radiation in industry, research and medical applications where radiation protection measurements are needed. The change affects the legal dose limits given in Council Directive 2013/59/Euratom, thus requiring careful consideration of how the dose limits should be set in future update of the directive.

The changes made to ISO standards and especially the adoption of the spectrometric characterization of radiation beams will improve the harmonization of calibration beams and their traceability to national references as well as the accuracy of the calibrations. The latter can be drastically improved allowing a more precise and comparable characterization of the measuring devices. Together with harmonized IEC standards this leads to the revision of the type tests carried out before the devices are put on the market.

This project will assess the consequences on radiation protection measurements and dosimeters caused by the adoption of new operational quantities proposed in the ICRU Report 95 and inform the manufacturers who will then be able to anticipate the prospected changes, by planning the recalibration, replacement, or adaptation of existing measuring devices. Thus, the transition from the present to the new operational quantities may be carried out in the most harmonious way possible. It is expected that the new operational quantities will be in force with the next update of Council Directive 2013/59/Euratom.

These changes in standards and quantities will require modifications to the dosimeters, either in the data processing algorithms, or in the physical design of the detectors, or both, to remain in compliance with the type test acceptance criteria. Adaptation of these criteria may be necessary in coordination with the improved measurement accuracy and new technologies discussed above.

Outcomes for the metrology and scientific communities

The implementation and harmonization of the spectrometry measurements will ensure reliable validation and calculation of laboratory-specific conversion coefficients. The guidance developed within this project will lead to a better understanding of uncertainties and comparable procedures and increasing therefore the confidence in radiation metrology and testing. Spectrometry will provide more accurate and complete data on radiation beams, which is currently available only to a few institutes, and thus will help proliferation of scientific knowledge, techniques and associated research. With expanded spectrometric capabilities, institutes can develop new radiation fields for future applications, needed to metrologically support developments in technology and regulation.

The evaluation of the impact of the new ICRU Report 95 quantities on the photon reference field standards will allow for an informed realization of calibration fields in the metrology institutes and calibration laboratories.

Outcomes for relevant standards

The project will contribute to the implementation and future updates of the ISO 4037 standards series and IEC standards that set requirements for radiation protection dosimeters by providing relevant data, guidance documents and validated limits for the performance of the dosimeters. Moreover, the implementation of the newly proposed operational quantities of ICRU Report 95 will have an impact on some of the limits given by the ISO 4037:2019-1 standard for matched and characterized reference fields and on the radiation doses recorded by the dosimeters. This will affect the personal doses that are monitored nowadays in compliance with Council Directive 2013/59/Euratom and will have an effect on the dose limits and the future update of this Basic Safety Standard and national implementations thereof.

Longer-term economic, social and environmental impacts

Stronger confidence in radiation protection dosimetry, both via the promotion of the implementation of the ISO 4037 standard series, and via the assessment of the impact of the new operational quantities defined in ICRU Report 95 on daily measurements in radiation protection, has the clear potential of making radiation protection dosimetry practices even better than presently; it also enables small laboratories to set up the reference beams according to the standard, thus increasing the availability of harmonized testing and calibration services. This provides an advantage to European-based dosimeter manufacturers on the global market.

Through the objectives of this project, procedures will be brought to maturity so that the implementation of the ISO 4037 standard series both at NMI/DIs and through European national networks of accredited dosimetry calibration laboratories will be facilitated and, therefore, requests of instrument tests and calibrations can be satisfied within Europe.

With the adoption of the new ISO 4037:2019 standard series throughout Europe, and with the related CMCs and services that derive from them, the European citizen would find him/herself in a context of measurement confidence and reliability, the basis on which citizen safety and security can hinge on.

More reliable, accurate, and harmonized tested instrumentation in radiation protection dosimetry, possibly supported by the well-informed technical adoption of the new operational quantities defined in ICRU Report 95, could also lead to a stronger European industry and an increased wealth that this can bring.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		June 2023, 36 months	
Coordinator: Teemu Siiskonen, STUK		Tel: +358975988318	E-mail: teemu.siiskonen@stuk.fi
Project website address: https://lmri-met.github.io/sites-guideradpros/			
Chief Stakeholder Organisation: ISO TC85		Chief Stakeholder Contact: Dr Yann Billarand, IRSN, France	
Internal Beneficiaries: 1. STUK, Finland 2. CEA, France 3. CIEMAT, Spain 4. CMI, Czechia 5. ENEA, Italy 6. GUM, Poland 7. IMBiH, Bosnia and Herzegovina 8. IPQ, Portugal 9. IRB, Croatia 10. IST, Portugal 11. PTB, Germany 12. SCK CEN, Belgium 13. TENMAK, Turkiye	External Beneficiaries: 14. EEAE, Greece 15. INM, Republic of Moldova 16. VINS, Serbia	Unfunded Beneficiaries: 17. Mirion, Finland	
Associated Partners: 18. QST, Japan			



Publishable Summary for 22RPT01 TracInd BVK-H Traceability for indentation measurements in Brinell-Vickers-Knoop hardness

Overview

Hardness is an important material property determined by measuring an indentation size realised on the tested material surface in the Brinell, Vickers and Knoop (BVK) scales. This project will investigate the indentation measurement phenomena to provide a better defined, more consistent, unified and reliable measurement and traceability methodology to overcome the inconsistency between NMIs and lower levels of indentation (hardness) measurements as well as between NMIs. The project outcomes will be used in the next generation of hardness definitions, instrumentation and standardisation to improve the accuracy of material testing in all engineering fields, including aerospace, automotive, health, industry, and research and development.

Need

Material properties are crucial factors in construction, design and engineering. Knowledge of the critical mechanical properties of materials used in production and construction is essential to prevent health and safety hazards, control the costs of production, and create better designed, healthy and consumer friendly products. This knowledge is obtained through the establishment of accurate, reliable and consistent reference standards for material properties at NMIs and a link to end-user measurements for the lowest level test in a workshop through a continuous traceability chain. Brinell, Vickers and Knoop testing methods are three of the most important ones used for testing the hardness of metallic materials. Hardness is determined in these scales by measurement of the size of an indentation made on the surface of the material with a known force and an indenter of known geometry and properties. There are many types of indentation measurement systems and methodologies. The indentation size measurement is completely dependent on the image magnification and processing instrument, the operator, and software if any. There are significant hardness measurement inconsistencies among NMIs, as well as between NMIs and testing laboratories due to lack of a well-defined methodology and specifications for the variety of indentation measurement instruments used. For example, optical microscopes with different numerical apertures (NAs) and software give different measurement results. This issue was demonstrated in 2005 at the NMI level in the CIPM Brinell Key Comparison, CCM.H-K2. At the lower levels of the measurement chain, the problem is much more evident. Traceable propagation of the reference value from NMIs to testing laboratories is not achieved due to the variety of simple devices used for testing without controlling all parameters. This project aims to overcome these critical problems by establishing the necessary methodologies and references for consistent, unified, reliable and traceable hardness indentation measurements from the NMI level to the testing laboratories.

Objectives

The overall objective of this project is to establish a traceable, consistent, and reliable indentation measurement methodology, considering the influence of measurement parameters and instrument specifications, for Brinell, Vickers and Knoop hardness scales. The specific objectives are as follows.

1. To establish universal definitions for indentation boundaries for Brinell, Vickers and Knoop hardness scales and to determine the required measurement parameters to be used with the highest accuracy

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: July 2024

and most commonly used instruments at the NMI level (scanning and optical) for the detection and measurement of indentation dimensions in line with relevant ISO standards.

2. To develop and validate stable reference indentation artefacts representative of the full Brinell, Vickers and Knoop hardness scales for propagation of traceability from NMI level to end users and to ensure inter-NMI comparability and consistency of indentation measurements.
3. To develop a methodology to ensure robust traceability for Brinell, Vickers and Knoop hardness measurements, from NMI to user level, through determination of the effect of influence factors on measurement results, and the development and validation of uncertainty models considering the most commonly used instrumentation at all levels and the applicable documentary standards. Additionally, to produce recommended technical specifications for manufacturers of hardness calibration and testing instruments.
4. To develop the software of an existing indentation measurement system (IMS) to automatise the determination of indentation locations and their measurements where possible and to determine the types of indentations that are suitable for such measurements and classify them.
5. To facilitate the take up and long term operation of the capabilities, technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), standards developing organisations (ISO), and end users (e.g. industry, regulators, manufacturers). The approach should be discussed within the consortium and with other EURAMET NMIs/DIs e.g. EURAMET TCs or EMNs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art and results

Development of methodology for Brinell-Vickers-Knoop indentation measurement:

Indentation measurement is generally realised with optical measurement devices, such as an optical microscope, with which two perpendicular diameters for Brinell, two diagonal length of Vickers and one diagonal length of Knoop indentations are measured. After inconsistent results were found in indentation measurements performed in the CIPM Brinell Key Comparison, CCM.H-K2, in 2005, the reason was found to be a significant effect caused by the use of lenses with different numerical apertures (NAs). It is now advised to use NAs equal to or bigger than 0.4 and measurement traceability is established via a certified stage micrometer (line scale). Yet, there is still no firm definition for the borders of indentations in all three scales (BVK) needed to determine the start and end points of the dimensional indentation measurements, which continues to be a source of measurement inconsistencies.

For development of a unified Brinell-Vickers-Knoop indentation measurement methodology, first of all the indentation definition was aimed to be investigated to decide about the border on indentation subject to measurement. For this reason a literature study was conducted and it was decided to measure a wide range of indentations in 3D with tactile and laser confocal measuring systems to measure the 3D surface areas of indentations by scanning and 2D optically to make a link between the real indentation and the optically imaged one. The methodology is constituted and the measurements are being conducted.

This project will establish a definition for the border of the circular shaped indents in the Brinell scale for different sizes and shapes (sink-in vs pile-up), for the corners of the square shaped indent in Vickers and the equilateral indent in the Knoop scale for different shapes (hard and soft). Then, specifications will be determined for recognising the borders and corners the indentations. At the conclusion of this project, end-users will have precise definitions of the measurands in the Brinell, Vickers and Knoop scales, and a standardised method for identifying their boundaries.

Development Brinell-Vickers-Knoop reference indentations:

The traceability in indentation measurement is established by calibration of the IMSs via a certified stage micrometer and a reference indentation on a hardness reference blocks, but these indentations are certified only by the NMIs or calibration laboratories with their own IMSs. The traceability in 2D (via stage micrometer) is easy to manage because the marking on the stage micrometer is more obvious and the imaging system and operator effect is much less. However, in actual indentation measurements, results vary according to system performance and imaging parameters due to the 3D characteristic of the indentations.

In this project a set of long term stable reference indentations for a wide range of hardness scales and levels was designed and the relevant hardness reference blocks were purchased and the reference indentations were realized on these blocks to be used as objects for investigation of the measurement methodology and to be accepted as transfer standards to be used for propagation of the traceability in Brinell-Vickers-Knoop indentation measurements.

Development of traceability chain from NMI to user level:

Hardness testing machines are produced without regard to considerations of traceability or correlation between the highest measurement systems and the simpler ones used in industry. There is lack of understanding of indentation definitions and traceability requirements in the applicable ISO and ASTM hardness standards which causes very significant deviations in implementation.

To develop a methodology to unify propagation of traceable and consistent indentation measurements from NMI and DI level to calibration and testing laboratories, and, furthermore, to draft recommendations for producers of hardness calibration and testing machines to ensure the compatibility of the machines they produce with higher level systems and the consistency of measurement results throughout the measurement chain a literature study was made. The most commonly used hardness instruments and hardness standards mainly within Europe were investigated and collected to establish the traceability methodology.

Automatisation of indentation measurements:

Indentation measurement systems at NMIs and DIs operate either manually or semi-automatically. Semi-automatic measurement enables measurement of the size of an indent in one direction after which the indentation must be manually rotated by 90° to make the second diameter or diagonal length measurement. This can be done only for one indentation although there have been trials to measure more than one indentation by specifying the location manually by the operator before their realisation. In entirely manual measurement systems, the border of indentations is decided by the operator which means there may be significant inconsistency between measurements performed by different operators.

In line with the realization of automatic measurements to eliminate operator effects and save time and labour during hardness measurement the literature on the measurement software present in use was searched. A preliminary design about the mechanic of the system present at TUBITAK UME Hardness Laboratory was made.

In this project, the indentation measurement system present at TUBITAK will be revised to improve its software and mechanical components to demonstrate full automatisation of indentation measurements. After the revisions, the locations of indents will be selected through the software and marked on a hardness block by the indentation measurement system (IMS) automatically, the indents will then be realised on the block by primary standard machines, and then the block will be placed in the IMS in its first position where the indentation locations were marked and saved by the software and indentation measurements will be realised automatically. This will be done for indentations for which edge detection with image processing are possible. Differently sized and shaped indentations will be analysed to determine the characteristics of those suitable for automatic measurements.

Outcomes and impact

The project had successfully established a stakeholder committee of 11 members representing accreditation organisations, standardisation bodies, equipment manufacturer and hardness testing machines users. The project provided training on "Hardness measurement methods" to 13 participants from the consortium. Also, the project's objectives were presented to EU institutions during the EURAMET TCM Meeting in Brussels, Belgium. An introductory presentation was made to the participants of the CIPM CCM WGH Meeting that was held in USA by online connection.

Outcomes for industrial and other user communities:

This project aims to improve the reliability of hardness tests at the industrial level by providing a better defined hardness (indentation) measurement methodology and sets of reference indentations agreed upon by the NMIs to provide traceability in BVK hardness scales. More importantly a methodology for traceability from the NMI level to the end user will be developed and based on this a set of recommendations for hardness calibration and testing instrument producers will be produced and disseminated. Uptake of the recommendations will enable a new generation of instrumentation for BVK hardness tests that produce results

that are more consistent with the higher level machines. On a wider scale, more accurate, reliable and consistent hardness measurements will benefit all industries in which such measurements are central to producing higher quality, durable and safer products.

Outcomes for the metrology and scientific communities:

The problem at the core of this project is the source of the traceability in hardness measurements, which is the definition of the indentation and the methodology for its measurement. The first outcome of the project will rely on a scientific approach to indentation phenomena to arrive at a universally applicable and clear definition of its borders, and accordingly, a uniform method for its measurement. This will enable more accurate and consistent measurement results, and consequently, improved hardness calibration and measurement capabilities (CMCs) at NMIs and DIs and a significant advancement in hardness metrology. Automatisation of hardness measurements, which will be demonstrated at an NMI in this project, also brings the prospect of faster and more cost-efficient measurements which are less affected by operator related errors.

Outcomes for relevant standards:

The main outputs of the project, including BVK indentation definitions, uncertainty models and methodology for establishment of traceability for BVK hardness measurements will be used as input to improve ISO 6506-1, ISO 6506-2, and ISO 6506-3 for Brinell, ISO 6507-1, ISO 6507-2, and ISO 6507-3 for Vickers, and ISO 4545-1, ISO 4545-2, and ISO 4545-3 for Knoop hardness tests, which currently have significant deficiencies. ASTM standards ASTM E92, ASTM E384 and ASTM E10 may also be improved as a consequence. Standardisation is envisioned to be one of the main conduits for widespread uptake of project outputs by industry and other end-users.

Longer-term economic, social and environmental impacts:

More consistent, reliable and traceable measurements of material properties will enable better, safer product design and manufacturing at a lower cost. Hardness tests are widely used material testing methods to obtain preliminary information about abrasion and strength properties of a material easily and quickly. The durability of a selected material is critical to the proper, predictable and safe functioning of manufactured products and components and the safety of the built environment.

Europe is one of the largest producers and exporters of highly engineered products, including aircraft, automobiles and other vehicles, defence systems, durable households' goods, etc, for which accurate and reliable knowledge of constituent materials is key to quality, and by extension, product marketability and demand. Having access to reliable and traceable hardness measurements will thus benefit European industry and its competitive position on global markets. More directly, the uptake of the recommended technical specifications for hardness testing machines by manufacturers will ensure that European producers will have an edge over their rivals in this field.

Failures of material in wastewater and waste disposal infrastructure and in systems for storage and transportation of toxic and hazardous substances are an instance of a source of environmental damage that could be ameliorated through better measurement of material properties so that their critical failure points are known with greater accuracy and reliability. Inconsistent and incomparable measurements, as is currently prevalent in hardness testing, introduce an unacceptably high level of risk of failure in systems needed for the safe handling of toxic substances. With better testing of hardness, and therefore of material durability, the infrastructure, systems and products that are relied upon to protect the environment can be expected to be more suitable for purpose, longer lasting and less likely to unpredictably fail.

Finally, safer and more reliable products, a reduction in the likelihood of hazards and accidents caused by product failure, and an appreciable improvement in the quality of the built environment will serve to enhance societal health and wellbeing.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2023, 36 months
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Project website address: www.tracind-bvk-h.org		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. TUBITAK, Türkiye	8. INM, Moldova	12. EASYDUR, Italy
2. BEV-PTP, Austria	9. POLITICO, Italy	13. LTF, Italy
3. CMI, Czechia	10. UNZE, Bosnia and Herzegovina	14. MPA NRW, Germany
4. GUM, Poland	11. ZAG, Slovenia	
5. IMBiH, Bosnia and Herzegovina		
6. INRIM, Italy		
7. PTB, Germany		



Publishable Summary for 22RPT02 True8DIGIT Towards a true 8-digit digitiser

Overview

This project addresses the development of a digitiser based on state-of-the-art analogue-to-digital converters (ADCs), operating from direct current (DC) to 100 kHz, meeting the demands for linearity, noise, and overall accuracy of high-level measurement applications that cannot be met using currently available digitisers. In this project research on the key techniques and technologies needed to underpin a follow-up full-scale project will be performed. An important aim is to provide research capacity building opportunities for developing NMIs/DIs on the design and characterisation of electronic measuring devices needed for a wide variety of interdisciplinary metrological challenges such as state-of-the-art DC measurements and advanced digital sampling techniques. This will enable these NMIs to join future full-scale projects.

Need

High resolution digitisers, used to convert electrical signals into digital form, which were first developed for metrology applications are now used for signal analysis in a wide range of applications including those in the automotive, aerospace, communications and medical fields. Extending the performance of digitisers beyond the current state-of-the-art, to deliver accuracy levels below the part per million level, will widen the range of signals accessible to traceable, reliable, and accurate measurement.

The core element of a digitiser is the analogue-to-digital converter (ADC). In 2016, the global analogue-to-digital converters market was valued at \$2.3 billion and is projected to double in value by 2027 growing at a compound annual growth rate (CAGR) of 6.7 % from 2019 to 2027. Dual-slope and $\Delta\Sigma$ ADCs share approximately 5 % and 20 % of the market, respectively. While high accuracy ADCs have traditionally found applications in the instrumentation and research arenas, they are rapidly and aggressively entering the medical (MRI, digital radiography, CT, ultrasonography), industrial and consumer (audio) markets.

Analogue-to-digital conversion is arguably the most widely used measurement technology worldwide, employed in almost all communication, smart (IoT) sensors, measuring devices and instrumentation regardless of the application area, up to redefined SI unit realisations. This is due to ADCs ability to provide the most straightforward conversion of analogue information obtained by sensors and transducers to its digital representation, which can then be further integrated into our increasingly digital world. The applications of digitisers often call for state-of-the-art capabilities across all performance parameters and there exist numerous examples in literature of attempts to optimise the performance of the best commercially available digitising solutions.

This project will extend the state-of-the-art in digitiser performance by using mixed technologies, mixed ADC architectures, powerful post-processing, and metrology class measurements to validate performance during all development steps. This will avoid the design compromises required for a full function digital multimeter on the one hand, and the fabrication challenges of an integrated circuit ADC on the other (such as power or size limitations, components price, chip area etc.). Such a development is a complex undertaking; therefore, this project proposes a two-step approach, (i) a capacity building project and (ii) a following full-scale JRP (in 2025 IEM call) to develop a functional metrology grade digitiser with a performance exceeding the current state-of-the-art.

Application fields for a digitiser with improved performance include, but are not limited to, audio, seismology, geographic surveying, industrial instrumentation and high-precision current control for accelerator magnets. Applications requiring novel digitiser solutions range from testing audio equipment, conversion of signals from high dynamic range seismic sensors, pressure and force gauges, weight cells, resistive thermometers and

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: May 2024

thermocouples, as well as superconducting quantum interferometers (SQUIDs), particle accelerator beam instrumentation, coil based magnetic measurements and quench detection in superconducting magnets. All these applications require one or more of the following characteristics which will be focus of the research: extremely high intrinsic dynamic range, low distortion, low noise, excellent stability and excellent linearity.

Objectives

The overall objective of the project is to perform bottom-up development and research underpinning the development of a digitiser featuring state-of-the-art performance, whose performance exceeds that of currently available digital multimeters (DMMs), digitisers or analogue-to-digital converters (ADCs).

The specific objectives are:

1. To identify at least 2 novel metrology grade ADC architectures for the DC to 100 kHz frequency band and develop comprehensive digital models covering integrating ADC (IADC), Sigma-Delta ($\Delta\Sigma$) and at least 1 mixed design. The models will include first and second order error mechanisms. This includes identifying key performance targets such as measurement error below 1 part per million, comparing the performance of the ADC architectures, and mitigating and/or compensating for their non-ideal behaviour by means of simulations.
2. To assess at least 2 designs for novel amplifiers (composite operational amplifiers (COPAs)) for integrator and front-end digitiser circuitry with zero drift, extremely high gain, low noise and error below 1 ppm, and to develop the metrological tools to evaluate the amplifier's performance. Additionally, to identify metrological methods for characterisation of resistors and capacitors for the amplifier's stability, tracking and nonlinear behaviour down to and below -120 dB total harmonic distortion (THD) and electronic switches for their injection currents and transients' stability.
3. To design and develop an ultra-quiet and stable low noise power supply, supplied from the mains supply but with negligible line interference noise, and applicable for all voltage and current spans needed by the metrology grade ADC architectures identified in objective 1.
4. To develop a precision (< 50 ps jitter) timing solution for the ADC architectures identified in objective 1, with a galvanically isolated external trigger, lock-in and internal clock frequency output, and to develop the metrological tools such as jitter and synchronisation measurement to evaluate ADC architectures' timing performance.
5. To facilitate the take up and long-term operation of the capabilities, technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), and end users (e.g. electrical power generators, manufacturers of medical imaging devices, ADC and DMM industry). The approach will be discussed within the consortium and with other EURAMET NMIs/DIs, EURAMET TCs or EMNs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art and results

Novel metrology grade ADC architectures

For high accuracy sampling measurements, a limited number of high-end digital multimeters and commercial digitisers are currently available in the market. However, their performance limits progress in precision low frequency applications.

This project will deliver key solutions and proofs of concept that will be used to underpin a follow-up project to develop a fully operational digitiser with improved linearity, dynamic range and accuracy. Development of new hybrid topologies with different ADC architectures will be supplemented with a parallel SAR architecture and the use of an ultra-pure sine wave or multi-tone sources will be implemented to improve digitiser linearity in AC regime.

Characterisation of composite operational amplifiers, linear components and switches

A key component in both IADC and $\Sigma\Delta$ ADC is the operational amplifier (OPA) which performs integration via a feedback capacitor. Single commercial OPAs do not meet the requirements for use as in a state-of-the-art IADC integrator or for zero-drift front-end design.

This project will deliver new topologies for composite operational amplifiers (COPAs) and build prototypes with superior performance to demonstrate that the current performance limitations of integrating and $\Sigma\Delta$ ADCs can

be overcome. Measurement techniques will be developed to characterise prototypes of COPAs. A different design of COPA will be delivered for a front-end circuitry with the lowest possible $1/f$ noise down to mHz and with high linearity and stability to cater for signal frequencies up to 100 kHz.

A precision ADC relies critically on selected linear components and switches that define its performance. However, characterisation of potential imperfections that are known in theory is lacking due to the considerable metrological challenge involved.

This project will deliver measurement techniques to characterise nonlinear behaviour of capacitors and resistors of different construction types and materials to the level required by the demanding objectives in this project. Switches will be tested for correct timing and charge injection repeatability and stability. Test beds will be constructed to isolate unwanted influences. Results will be used to update the models and determine their effect on the modelled ADC performance.

Ultra-quiet, stable and line interference free power supply

Power line interference, once introduced in the instrumentation is practically impossible to eliminate and consequently these interferences have a negative impact on precision sampling measurements. Available DC-DC supplies today with multiple isolations between the input and output can achieve lower leakage currents than transformer-based power supplies, but are limited in achievable output currents. Hence, the most demanding measurements require the use of batteries as a power source despite the limitation of their restricted operating duration.

This project will develop a novel power supply solution with insignificant line related interferences while allowing continuous operation. Potential malfunction identification and protection will be incorporated to protect sensitive loads.

Precision timing solution for ADC architectures

Accurate timing is essential in IADC and $\Delta\Sigma$ ADC designs, while perfect synchronisation is required for precision sampling measurements. Currently, no IADC or $\Delta\Sigma$ digitisers provide for true synchronisation.

This project will deliver a timing solution including low jitter multiple external triggers, lock-in and synchronisation with 100 MHz clock system frequency and galvanic isolation. This timing solution will provide necessary tools for a true synchronisation, that would be applicable also for new IADC architecture.

Outcomes and Impact

A stakeholder committee drawn from NMIs, instrumentation manufacturers, IC manufacturers, research centres and electronic designers has been formed. Three collaborators have joined the project. A project web-site has been established (<https://true8digit.eu/>). An overview of the project's objectives and work plan was presented to IEEE TC10 'Instrumentation and Measurement/Waveform Generation, Measurement, and Analysis'. IEC TC85-WG22 'Waveform parameter measurements' and IEC TC47-SC47A 'Integrated Circuits' have also been informed about the project. Oral presentations on the project have been made at the meeting of the EURAMET Technical Committee on Electromagnetism and at the international symposium 'High Performance Digitisers and DC Metrology'. A paper entitled 'Measuring Wideband Nonlinearity in Analog to Digital Converters' has been accepted for the IEEE I²MTC conference and will be presented at the conference in May 2024.

Outcomes for industrial and other user communities

Industrial end users and stakeholders will directly benefit from the project outputs, such as advanced instrumentation with interference-free power supplies, cost effective selection of passive components for sensor/transducers and instrumentation, as well as precision isolated timing solutions for synchronised measurement systems. The project will provide key techniques and develop technologies to improve available state-of-the-art digitiser performance. An improved dynamic range would benefit seismology and geophysical surveying, where seismic sensors already provide a signal with such high dynamic range that even existing high-resolution digitisers present a bottleneck in the acquisition system.

This project will directly liaise with industrial stakeholders via the formation of a stakeholder committee. This group will include representatives from instrument and DAQ manufacturers, test and calibration service providers, chip manufacturers and research institutes, and will help the project's results to directly impact such representatives.

This project will also produce and publish two reports for end-users:

- Report on characterisation of non-linear effects in resistors and capacitors and stability of residual effects in switches.
- Report on characterisation of timing and synchronisation solution

The project's outcomes will be disseminated to instrument and data acquisition (DAQ) manufacturers and calibration laboratories by organising at least one international workshop aimed at collaborators and stakeholders, where key developed solutions will be presented, targeted to precision digitising, their wider applicability and impact to precision instrumentation and measurements.

Outcomes for the metrology and scientific communities

The project will improve and extend electrical sampling metrology for signals from DC to frequencies beyond the audio range, leading to innovation in the development and improvement of the precision measuring systems and instrumentation. The project's outcomes will provide the basis for improvements in the realisation of new SI units, and applications requiring precise synchronisation and amplitude/phase accuracy at or below the 1 ppm level, such as power and energy measurement, smart grid and power quality reference instrumentation calibrations, impedance bridges, AC Josephson, as well as in other measurement fields such as accurate readouts for highly stable temperature sensors. This will have a significant impact on calibration laboratories and their customers.

In the area of digitisation and instrumentation, knowledge transfer from experienced NMIs to those less experienced on how to benefit from digitisation and how to design precision measurement systems will be highly beneficial.

The scientific community will benefit from improved readout from sensors, especially from intrinsically low-noise devices like superconducting magnetometers, particle accelerator beam instrumentation, digital integrators for detecting coil-based magnetic measurements and quench detection in superconducting magnets. Such applications are often driven by highly specific requirements that cannot be summarised, but they all call for a best achievable linearity and stability in the final data conversion stage.

Major scientific impact will be provided through the publication of project results in scientific journals and presentations at key conferences. The project will disseminate all key results directly via relevant EURAMET technical committees and further to accredited calibration laboratories and scientific community via conference presentations, scientific publications, web page and appropriate social media outlets.

Outcomes for relevant standards

The project will investigate new test methods required for testing ADC performance beyond the current state-of-the-art for linearity and stability. This will impact IEEE standard 1241, and the consortium will communicate directly with IEEE committee TC10 as this is responsible for all IEEE ADC and DAC related standards. Dynamic performance testing will be developed through the use of ultra-pure sine wave and multi-tone sources. This will be relevant for IEC 60748-4-3, which covers dynamic criteria for analogue-to-digital converters. The consortium will liaise with IEC TC47 SC47A as this is the committee responsible for maintenance of this standard. This is also relevant to work being undertaken in IEC TC85 WG22.

Longer-term economic, social and environmental impacts

The technological environment in which science and industry operates depends, to a large extent, on our ability to measure phenomena in the physical world. To do this requires a sensor which converts the measured quantity into a measurable analogue signal and a digitiser which converts this signal into a number.

The majority of the processing of analogue signals now takes place in the digital domain. The improved digitisers envisaged in this, and a potential associated follow-on project will, in time, filter down to everyday applications such as medical diagnostics, energy conservation, security and the internet of things.

Improvements in the precision, speed and accuracy of digitisers over the years have allowed us to measure a wider range of quantities with ever greater sensitivity, with consequent benefits in fields such as manufacturing, medical diagnostics, smart electrical grids, energy conservation and environmental protection. Nonetheless, there is still a wide variety of signals, for example, in the fields of power quality, geophysics, acoustics, whose accurate measurement lies beyond the capability of even the best digitisers that are currently available.

Improvements in ADCs, which provide the core element for digitisers, continue to be made. These advances can be exploited to produce metrology-grade digitisers, whose performance surpasses those of existing devices. To do this, every functional element of the digitiser, the signal conditioning block, the ADC itself, the power supply and the timing circuitry, must be optimised.

This project supports the long-term transition of EU toward digital transformation. The use of next-generation digitisers is a prerequisite for improved instrumentation and data acquisition systems, which are embedded in manufacturing for process control and quality assurance. Digital instrumentation is becoming standard in the power grid, where this project's outcomes in accuracy and timing will provide for an improved detection and localisation of critical events. New improved instrumentation is needed where the measurement of difficult-to-measure phenomena is necessary to make progress in the field.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months
Coordinator: Oliver Power, NSAI Tel: +353 1 808 2610 E-mail: oliver.power@nsai.ie		
Project website address: https://true8digit.eu/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. NSAI, Ireland	10. CERN, Europe	14. UNISANNIO, Italy
2. CMI, Czechia	11. CTU, Czechia	
3. FER, Croatia	12. INTI, Argentina	
4. INRIM, Italy	13. LeftRight, Slovenia	
5. IPQ, Portugal		
6. JV, Norway		
7. PTB, Germany		
8. SIQ, Slovenia		
9. VSL, Netherlands		
Associated Partners:		
15. SC, United Kingdom		



Publishable Summary for 22RPT03 MultiFixRad

Improving the realisation of the kelvin by multiple fixed-point radiation thermometry

Overview

Highly accurate and traceable high temperature measurements are critical to a number of European industries, including metallurgical industries, glass, graphite and fertiliser production. Currently, there are regional gaps in the dissemination of the temperature scale with primary techniques at high temperatures. The *mise-en-pratique* of the new definition of the kelvin (*MeP-K*) offers new possibilities to realise and disseminate thermodynamic temperature using multiple high-temperature fixed points to calibrate a radiation thermometer, which is then used as an interpolating instrument. The project aims to assist 6 less experienced European national metrology institutes and designated institutes (JV, RISE, DFM, CMI, SMU, and UL) in establishing their own primary reference scales for thermometry using this approach. The improved high-temperature measurement standards will respond to industrial needs in the countries and enable participation in development projects for fundamental thermometry at high temperature, and at the highest scientific level.

Need

The recent redefinition of the kelvin, and the new *MeP-K*, opens up a new pathway for dissemination of the temperature scale. The most common instruments for disseminating temperature remain thermocouples for temperatures up to around 1500 °C, but these require calibration against primary references. The less experienced institutes in this project (JV, RISE, DFM, CMI, SMU and UL) are all well-established intermediate level national metrology institutes (NMIs) and designated institutes (DIs) in Europe, but they currently lack a realisation of high temperature primary standards. The participants represent countries with substantial production, processing, and manufacturing industries with expressed needs for improved high temperature standards, including the metallurgical industry, manufacturing of building materials and H₂ production.

Following the recent redefinition of the kelvin one of the most promising primary reference standards for high temperature is to interpolate between high temperature fixed points, whose transition temperatures have been established with high accuracy, using a radiation thermometer as the interpolation instrument. However, the method has not yet been implemented on a large scale outside the major NMIs. An important pillar of the metrological community is the ability to compare results across different institutions and countries, but this requires that a certain number of institutes are capable of realising the quantity to be compared. To address these aims some less experienced NMIs/DIs need to develop primary thermometry capabilities, including the ability to construct, characterise, use and maintain fixed points intended for radiometric applications, and to establish a primary temperature scale in line with the revised *MeP-K*. By taking a coordinated approach this will help the European metrology community to improve its robustness, but at the same time avoid fragmented and uncoordinated capacity building. The consortium will create nascent regional centres of excellence in the field, by coordinating the activity in the Scandinavian and central European regions, respectively.

Report Status:
PU – Public, fully open

Publishable Summary

Issued: April 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



Co-funded by
the European Union

**METROLOGY
PARTNERSHIP**



Objectives

The overall objective of this project is to endow six European NMIs (JV, RISE, DFM, SMU, CMI and UL) with the competence and resources to realise a primary high temperature scale at the highest level, in accordance with the revised MeP-K. The specific objectives are:

1. To transfer knowledge to the less experienced institutes on the theoretical and experimental aspects of the realisation of the ITS-90 by extrapolation from a single fixed point. An important part of this includes knowledge about the characterisation of the radiometer used to extrapolate temperature, such as its size-of-source sensitivity, linearity and spectral response.
2. To construct a set of medium- to high-temperature fixed points for radiation thermometry adapted to the technical means of less experienced NMIs/DIs. This includes assessment of the quality of the cells and experimental determination of the optimal thermal conditions for their use.
3. To realise the MeP-K through the application of the multi fixed point scheme using a variety of radiation thermometers and temperature ranges in accordance with the needs of less experienced NMIs/DIs, and to compare several realisations to the ITS-90. The target uncertainty of the realisations is 0.6 °C at 1500 °C and 1 °C at 2000 °C.
4. To perform an interlaboratory comparison, aiming to establish linkage to key comparison CCT-K10, to underpin improved calibration and measurement capabilities (CMCs) for participant laboratories in the field of radiation thermometry.
5. To facilitate the take up and long term operation of the capabilities, technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), standards developing organisations (e.g. CIPM CCT, EURAMET TC-T), and end users (e.g. metal forming, building insulation, and steam reforming).

Progress beyond the state of the art and results

Knowledge transfer on the theoretical and experimental aspects of using ITS-90 and high-temperature fixed points

Above the freezing point of Ag (961.78 °C), the ITS-90 [1] is defined by extrapolating the Planck radiation from a blackbody at either the Ag, Au or Cu fixed points. While many laboratories perform some sort of scale dissemination this way, few have the capabilities to carry out a thorough characterisation of the pyrometer used in the extrapolation, including control of the linearity, spectral response and size-of-source (SSE) sensitivity. The kick-off meeting, which was held in Prague in June 2023, included a workshop where the experienced partners LNE, CNAM and TUBITAK gave comprehensive presentations of the state-of-art. This included a historical overview of the development of high temperature eutectic fixed points, a thorough description of the current ITS-90 scale and how it differs from the multiple fixed points technique, and an overview of uncertainty contributions that needs to be taken into account. A practical laboratory session provided insights into basic characterisations of pyrometers. The partners have collected information on the present capabilities of the less experienced institutes, and this will be used to identify opportunities for smart specialisation in the Scandinavian and the central European regions.

Construction of medium and high-temperature fixed point cells

High temperature fixed points are non-trivial to construct, characterise and use. Some fixed point cells are prone to damage, which means that a laboratory must expect to regularly replace or characterise their cells. In January 2024 the partners gathered at CNAM in Paris for a practical walk-through of fixed point construction and a Cu cell and a Co-C eutectic cell were constructed and characterised. The partners discussed details regarding the analysis of data, in particular how to identify badly constructed cells, how to assign the melting temperature, and which data features can indicate issues such as too large thermal gradients in the furnace used to realise the phase transitions.

Metals (Al, Ag, Cu, Fe, Co, Pd, Pt and Re) necessary to construct cells have been ordered and partly delivered. The cells constructed will include Al (660.323 °C), Ag (961.78 °C), Cu (1084.62 °C), Fe-C (1154 °C), Co-C (1324.24 °C), Pd-C (1492 °C), Pt-C (1738.28 °C) and Re-C (2474.69 °C). The graphite parts that will be used to build the actual fixed point cells include a crucible, blackbody y and a lid, and have been ordered from a known supplier.

To realise the new MeP-K through a multi-fixed point scheme

The current scale realisation at the participants is either based on thermocouple calibration at fixed points from the intermediate range from 660 °C (Al freezing point) and upwards, or radiometric extrapolation in line with ITS-90, but with relatively high uncertainties. None of the less experienced institutes have a primary realisation of temperature according to the revised MeP-K. In this project the less experienced institutes will be equipped with the experience, skills and knowledge to implement a continuous temperature scale using interpolation between 3 or more high-temperature fixed points. The target uncertainty of the realisations is 0.6 °C at 1500 °C and 1 °C at 2000 °C. The consortium will also explore an interpolation scale for intermediate temperatures, which aims to rival thermocouples from 660 °C and upwards. New measurements will be carried out on the aluminium and silver points, using the extrapolation technique of ITS -90 to scale the radiometric measurements down from the Cu point.

To perform an interlaboratory comparison with the possibility of linkage to CCT-K10

The experienced partners LNE and CNAM have written a comparison protocol to be used in the comparison. In addition, circulating instruments have been identified: a furnace and two Cu fixed point cells, which will serve as a traveling benchmark to detect drift in the instrument under calibration. The traveling pyrometer is in the process of being acquired by CNAM.

The comparison protocol will be submitted to the working group for key comparisons under the CCT (CCT WGKC). If the review results in requests for modifications these will be implemented before the launch of ILC, in order to obtain official approval. The aim is to establish a formal link to the CCT-K10 via the French institutes (LNE and CNAM). The results of the comparison will also provide a first testcase for the new MeP-K. If successful, the comparison will strengthen the idea that the interpolation scheme is a viable path to realise a thermodynamic temperature scale beyond the highest-ranking institutes.

Outcomes and impact

A project website has been established which includes news and technical details of the project and consortium, information on events and presentations; and a LinkedIn group has been set up to exchange information among the members of the project and the end -users. A series of training sessions has been organised during the kick off meeting.

Outcomes for industrial and other user communities

The new capabilities established in this project will aid regional accredited laboratories and industrial stakeholders. A number of energy intensive industrial processes, such as metallurgical processing, fertilizer, glass and graphite production, take place at high temperatures in excess of 1000 °C, where the accurate control of temperature may affect the quality of the end product. With improved reference standards, the NMIs and DIs will be able to supply stable and precise calibration services to regional customers, which in turn will enable improved temperature measurements in industrial applications. Precise reference standards pave the way for new techniques for applied thermometry, which in turn may lead to improved process control. The project will demonstrate examples of the dissemination of the new scale at three industrial environments during the project. One method will be by transfer using an interpolation instrument calibrated at fixed points, which is close to the traditional way to transfer traceability. A second method will deploy a calibrated fixed point at the factory to enable a local calibration directly against this point. If successful, this will directly enhance the temperature measurements at the end users.

Outcomes for the metrology and scientific communities

The direct outcome of this project will be to assist six less experienced European NMIs and DIs (JV, RISE, DFM, CMI, SMU and UL) to establish a primary temperature scale in line with the revised MeP-K that followed the redefinition of the kelvin in 2019. In particular the participants will implement the interpolation scheme, where precise radiometers are used as interpolation instruments that are calibrated using three or more temperature fixed points. This will enable these institutes to (i) be in a position to submit CMCs for new or improved calibration services within the range 961.78 °C to 2474.69 °C, (ii) help disseminate a more precise high temperature scale in Europe, and (iii) contribute to future research and collaborations in high temperatures, such as the European Partnership on Metrology calls on Industry, Integrated European Metrology and Fundamental Metrology. The less experienced NMIs/DIs will all benefit from a potential

opportunity to link to the CCT-K10 key comparison, as this will help document their measurement capability at the end of the project and allow them to register updated and improved CMC values in the Key Comparison database. An important aim with this project is to foster regional collaboration and specialisation within EURAMET. The consortium consists of European NMIs and DIs that conveniently cluster in two regions, the Scandinavian and central European regions. This enables the consortium to create centres of excellence to cover regions beyond individual countries. The strategic outlook of CCT for the 2020s calls for further development and dissemination of primary thermometry techniques, and this project will enable the less experienced institutes to contribute to this work.

Outcomes for relevant standards

The new MeP-K acknowledges the interpolation scheme as a primary thermometry method, but it has not yet been implemented beyond the largest NMIs. The project will produce the first technical guide for the implementation of a thermodynamic temperature scale. The aim is for this to eventually be a EURAMET guide, and it will be developed to fulfil the needs expressed by the EURAMET TC-T but also the CCT. The experience from work within the project is expected to inform the CCT on relevant aspects of the new MeP-K.

Longer-term economic, social and environmental impacts

There are a number of industrial processes with high importance for the green transition that involve processing steps at high temperature, which are widely employed in the countries represented in the consortium. Examples range from the manufacturing of solar cells, steam reforming for H₂ production, the production of graphite for Li-ion batteries, to manufacturing building insulation materials. High temperature measurement is also important in combustion processes, such as ICE engines, waste incineration or power plants. Improved high temperature standards and measurements are the basis for optimising these processes, which in turn may improve product quality, enhance efficiency, and reduce the resource footprint of the processes.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2023, 36 months
Coordinator: Åge Andreas Falnes Olsen, JV Tel: +47 988 10 363 E-mail: aao@justervesenet.no		
Project website address: https://projects.lne.eu/jrp-multifixrad/		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. JV, Norway	10. DTU, Denmark	-
2. CMI, Czechia		
3. CNAM, France		
4. DFM, Denmark		
5. LNE, France		
6. RISE, Sweden		
7. SMU, Slovakia		
8. TUBITAK, Türkiye		
9. UL, Slovenia		

Publishable Summary for 22RPT04 RFMicrowave2

Development of RF and microwave metrology capability II

Overview

In recent years, the requirements from industrial and other sectors for the reliable measurement of radio frequency (RF) and microwave (MW) parameters have increased as technology has developed and become more innovative. However, the capability to address the requirements of these stakeholders only exists in a limited form in some national metrology institutes (NMIs) and designated institutes (DIs) with emerging capabilities. This project will develop a robust and sound approach for the measurement of RF & MW quantities and the evaluation of the associated measurement uncertainties, that goes beyond the achievements in the EMPIR project 15RPT01 RFMicrowave.

Need

Currently, new technologies in the fields of health care, security, traffic management, environmental monitoring, advanced industrial production, quality testing and communications require novel measurement methods and devices, including those involving RF&MW technologies. The frequencies, complexity of systems and data rates are continuing to increase which brings new challenges to the underpinning metrology. The necessary progress in RF to THz metrology on the European level is only achievable through effective cooperation between European NMIs, DIs and their stakeholders. There are several crucial fields, such as measurement of RF power and related quantities e.g., attenuation, electromagnetic field intensity and antenna parameters measurements which influence the measurement capability and traceability in many other areas. With the emergence of 5G, frequencies above 18 GHz are being used more widely, and electromagnetic compatibility (EMC) testing will be needed at these frequencies, requiring improvements in the calibration of antennas and electromagnetic field probes. A unified approach to measurement uncertainty evaluation is needed to compare the results of interlaboratory comparisons and to claim uncertainties for commercial calibration services.

The range of complex measurements required in both the time and frequency domains will continue to grow to meet the needs of the fast technological progress in many areas. In addition to establishing traceability and reducing the uncertainty of existing quantities, there are measurement and metrology challenges that are currently not supported by leading and experienced NMIs. In some cases, CMCs do not yet exist in the BIPM's KCDB for particular quantities because their traceability to basic SI units is very complex. Such challenges have been identified by the EURAMET TC-EM SC RF&MW, CCEM, CEN/CENELEC and others and include new nano-devices, on-wafer measurements, nonlinear VNA measurements, performance evaluation of alternative EMC test methods, efficient antenna calibration algorithms, high-speed differential measurements and signal integrity, over-the-air measurements in wireless communications and many others. Effective cooperation of European NMIs/DIs on these big challenges and the development of new and improved measurement techniques, procedures and standards require the capability gap among NMIs/DIs to be reduced, which would also improve the ability to fulfil the needs of fast-growing local industries in some countries.

Objectives

The overall objective of the project is to improve the European measurement and research capability for RF&MW metrology and to strengthen the potential for future cooperation among European NMIs, DIs and their stakeholders.

The specific objectives of the project are:

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: December 2024

1. To develop traceable targeted RF and MW metrology capability for RF/MW power, attenuation (transmission coefficient) and return loss (reflection coefficient) (S-parameters) in the frequency range up to at least 18 GHz in institutes with less experience. The development will be tailored to the defined industrial and economic needs of participating institutes.
2. To develop measurement and calibration capabilities for antenna parameter measurements, in particular the antenna factor, in the fields covering communications and electromagnetic compatibility (EMC) in the frequency range up to at least 18 GHz in institutes with less experience.
3. To develop measurement and calibration capabilities for electromagnetic field intensity measurement in the frequency range up to at least 30 MHz in institutes with less experience.
4. To develop a unified approach to measurement uncertainty evaluation that will reflect the state-of-the-art methods currently being developed in the framework of other European research projects. The approach will cover full uncertainty evaluation for all metrology capabilities developed from the first three objectives.
5. To facilitate the take-up and long-term operation of the capabilities, technology and measurement infrastructure for RF, MW and EMC measurements developed in the project, by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), and end users (e.g., industry, instrument manufacturers, regulators). The approach will be discussed within the consortium and with other EURAMET NMIs/DIs, e.g., via EURAMET TC-EM and EMN MATHMET, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art and results

Metrology for state-of-the-art technologies in RF and microwave field presently exists in relatively few European countries, and the capability level of NMIs/DIs in particular areas differ across countries for both historical and economic reasons. This project follows up on the EMPIR project 15RPT01 RFMicrowave which ran from 2016 to 2019. In that project less experienced NMIs/DIs gained expertise in three areas: (i) S-parameters, (ii) RF power measurements, (iii) calibration and testing procedures for EMC using RF&MW metrology. This project will focus on topics and aspects that were not addressed in the 15RPT01 and will go beyond the state-of-the-art in several areas:

Advanced RF power measurement techniques

RF power traceability at the primary level is provided using a calorimeter, which is only available in several developed NMIs. Moreover, calorimeter measurements become very cumbersome and expensive as the frequency increases above 50 GHz, and the technique is only available for power sensors based on a thermal conversion principle. In other cases, secondary-level techniques for the calibration of power sensors are used. Another commonly measured quantity is RF attenuation, however primary level attenuation measurements require traceable standards, which are limited to MHz frequencies. Measurement of attenuation at GHz frequencies and reliable measurement of high attenuations (>100 dB) is therefore problematic, particularly in less experienced NMIs. More affordable and practical techniques are therefore required. This project has already established capabilities for the automatic measurement of RF power and assessment of the Monte Carlo simulation methods for the calculation of uncertainties, which was validated by a comparison of direct RF power measurement using the AutoRFPower software developed in the project. The establishment of (i) RF power measurement and power sensor calibration (calibration factor) using a vector network analyser (VNA) and the VBPS tool is ongoing, and (ii) the measurement of S-parameters using VNAs and the measurement of attenuation using a spectrum analyser will start in spring 2025.

Antenna measurements

Antenna measurements are very demanding due to the level of knowledge of the underlying principles of electromagnetic field theory, measurement equipment and laboratory facilities required. Although calibration of basic quantities such as antenna gain is well established in more experienced NMIs at frequencies up to tens of GHz using conducted tests (i.e., the antenna is generally connected to the analyser using a cable), currently there are significant challenges in the area of 5G communications for measurement of quantities over the air, i.e., without the use of cables. Several new traceable antenna calibration techniques have been already established in the project (i.e., monopole and loop antenna calibration) and the comparison of different calibration methodologies in the frequency range 9 kHz – 40 GHz are currently ongoing. The validation of the

new capabilities is currently ongoing by intercomparisons. The project will further produce a best practice guide on the calibration of antennas in different set ups.

Electromagnetic field measurements

Electromagnetic field measurements are also very demanding and require considerable experience. Low-frequency electric and magnetic field generation and measurements are available in some less experienced NMIs up to frequencies of tens of kHz, however, measurements at MHz or even GHz frequencies are currently offered only in more experienced European NMIs. Project partners are continuing to improve their capabilities for (i) electromagnetic field calibration in the frequency range from 10 Hz up to 40 GHz, including the generation of electromagnetic fields, and (ii) the measurement of electromagnetic field intensity, including reducing the causes of deviations between calibration results obtained from different realisations or different laboratories. New field realizations have been established in some institutes (parallel plate capacitor, Helmholtz coils, pyramidal cell, μ TEM cell) with the help of more experienced partners which will be later validated by intercomparisons. Finally, a best practice guide on how to build calibration capability for electric and magnetic fields over a full frequency range (i.e., 10 Hz – 40 GHz) will be produced. At the conclusion of the project, several less experienced NMIs will be able to build their own simple realisations of electromagnetic field intensity (parallel plate capacitor, Helmholtz coils, TEM cell) or utilise commercial solutions (fully anechoic chamber).

Unified approach to measurement uncertainty evaluation

During the training sessions related to RF power measurement techniques, antenna measurements and electromagnetic field measurements organised early after the start of the project, an introduction to more advanced measurement uncertainty evaluation techniques was given by more experienced partners in particular fields. In case of RF power measurements, a unified method for evaluation of measurement uncertainty has been used in the interlaboratory measurement comparison using the AutoRFPower tool and the VBPC tool will be used for calibration factor measurements of power sensors. Cooperation with the European metrology network MATHMET is sought for further advancement of measurement uncertainty techniques used in the project in next years.

Outcomes and impact

At the end of this project, participating NMIs will have gained the necessary knowledge and skills to provide new or enhanced RF&MW services for their stakeholders. To ensure this, each participants' activities in the project have been designed according to their and their stakeholders' particular needs.

A project website has been established which includes news and technical details of the project and consortium, information on events and presentations; and a LinkedIn discussion group and an X (previously known as Twitter) group have been set up to exchange information among the members of the project and the end-users. A series of training sessions has been organised during the kick off meeting and the month 18 meeting.

Outcomes for industrial and other user communities

The enhanced measurement capabilities in particular NMIs and DIs will help them to better engage with local industries and government bodies and address their needs. Accredited calibration laboratories that obtain traceability from NMIs and DIs as the ISO 17025 requirement will be able to send their measurement standards directly to a local NMI/DI rather than to NMIs/DIs abroad. EMC test laboratories across Europe will benefit from enhanced capabilities of NMIs and DIs in antenna measurements and electromagnetic field measurements. Best practice guides on antenna measurements and electromagnetic field measurements will be publicly available for stakeholders via the project website and open-access repositories. On-going interaction with stakeholders will be achieved through the project website, the LinkedIn discussion group and an X group, and the project participants will also engage with target end-user communities via the project's workshops, meetings with technical working groups, as well as presenting the project's results at metrology conferences and in scientific publications.

Outcomes for the metrology and scientific communities

The project will establish new calibration services in particular NMIs and DIs (e.g., measurement of the calibration factor of power sensors using a VNA, measurement of high attenuation, calibration services for antennas, measurement of electromagnetic field intensity). Both small institutes that wish to develop new competences and also larger ones aiming to improve/broaden their capabilities will benefit from the project

outputs. The project outputs including results of interlaboratory comparisons will be beneficial for extending accreditation scopes of NMIs in the future, and for supporting and establishing new CMC entries in the KCDB database. Gaining more experience with basic antenna measurements and calibration of antennas for EMC applications in this project will also allow participants to take part in more advanced research projects (e.g., in the European Partnership on Metrology). The individual strategies developed for each participant for the short and long-term developments of their research capability in microwave metrology will be discussed within the consortium and in the meetings with EURAMET TC-EM SC-RF&MW. These strategies will particularly focus on regulatory support, research collaborations with the members of the European research community, quality schemes and accreditation of the NMIs.

Outcomes for relevant standards

This project does not aim to directly influence existing international standards nor contribute to the development of new ones, although efforts will be made to contact standardisation bodies and share the results of the project with them. Project participants that are members of local standardisation working groups will inform those groups about the progress of the project regularly. The project will support active participation in committees such as the EURAMET TC-EM SC-RF&MW or EMN MATHMET. Stakeholders from outside the EURAMET community will be contacted (e.g. WELMEC) to learn about their own needs and how the project could support them, even indirectly.

Longer-term economic, social and environmental impacts

Mutual cooperation of project participants will create new personal connections and strengthen existing ones, so that the joint research efforts among European countries will be more efficient. The less experienced institutes will be better prepared for participation with leading European NMIs in challenging future project calls within the European Partnership on Metrology together, such as the 2025 Health and Integrated European metrology call and the 2026 Fundamental and Industry call.

Automated RF power measurement with measurement uncertainty calculation will significantly speed up the calibration process and thus save money for accredited calibration laboratories and their customers. Better RF&MW capability in NMIs and DIs may, in the long-term, help to harmonise RF&MW metrology and EMC tests, which will help European producers and manufacturers of automotive, consumer electronics, digital and communication equipment etc. to compete in the global market. The calibration methods for antennas and field probes will indirectly enable electronic device manufacturers to obtain conformity more readily with related standards; helping to reduce the costs associated with conformity assessment.

More reliable measurements of RF power, antenna parameters and electromagnetic field intensity will be beneficial for energy savings and the protection of citizens against non-ionising radiation from telecommunication base stations, which are very densely distributed in the forthcoming 5G networks, especially in city environments. The 5G base stations work with high power levels and use complicated multi-beam antenna systems to cover large areas with a quality signal. The ability to measure RF power and antenna parameters reliably may allow the communication systems to be designed with a smaller power margin and thus be more energy efficient. The 5G base stations' radiation became a source of public concern and have been identified as a potential health risk by the ICNIRP. Reliable measurement of electromagnetic field intensity in the vicinity of base stations (e.g., using the code-selective method) will allow potential violations of the recommended radiation levels to be identified.

The project's results will have an indirect social impact through the improved quality and safety of electronic devices. In addition, electromagnetic interference (EMI) radiated from incompatible devices can be considered as environmental pollution and can have environmental consequences that are comparable to vehicle exhaust emissions or wastewater discharge. The environmental consequences can also cause disturbance to machines and, exposure of the population to high electric and magnetic fields.

List of publications

Cetinkaya, A. et al (2024) 'Uncertainty Calculation as a Service: Integrating Cloud-Based Microservices for Enhanced Calibration and DCC Generation', *Sensors*, 24(17) p. 5651. Available at <https://doi.org/10.3390/s24175651>

Cetinkaya, A. et al (2024) 'Uncertainty Calculation-as-a-Service: Microservice-Based Metrology Applications', *18th European Conference on Software Architecture*. Available at <https://doi.org/10.5281/zenodo.14021144>

Lapuh, R. et al (2024) 'Uniform magnetic field coils construction optimization', *2024 International Symposium on Electromagnetic Compatibility*. Available at <https://doi.org/10.5281/zenodo.14020254>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 May 2023, 36 months
Coordinator: Martin Hudlíčka, CMI		Tel: +420 266 020 174
Project website address: https://rfmwii.cmi.gov.cz/		E-mail: mhudlicka@cmi.gov.cz
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CMI, Czechia	9. KORAL, Italy	13. PTB, Germany
2. GUM, Poland	10. LeftRight, Slovenia	
3. IMBiH, Bosnia and Herzegovina	11. METU, Türkiye	
4. NSAI, Ireland	12. SPARK, Türkiye	
5. RISE, Sweden		
6. SIQ, Slovenia		
7. Trescal, Denmark		
8. TUBITAK, Türkiye		
RMG: -		

Publishable Summary for 23CBC01 CaBuCo Capacity building coordination

Overview

The landscape of the European metrology infrastructure is constantly changing with emerging metrology systems or fields of measurements. This project aims to support EURAMET's members and associates to develop a balanced and integrated metrology system in the participating countries. It will provide support and coordination of existing capacity building instruments (Researcher Mobility Support, Mentoring Scheme Award, Training events) to address key metrological challenges and build capacities through knowledge transfer activities.

Need

The capabilities of EURAMET National Metrology Institutes (NMIs) and Designated Institutes (DIs) vary from country to country. Many European NMIs and DIs represent the cutting edge of global measurement expertise, actively participating in research that develops new measurement technologies and new realisations of SI units. These institutes play a leading role in supporting global competitiveness of the European economy as well as the development of measurement technologies required by modern society. Some institutes however are at an earlier stage of development, focusing more on service-oriented approaches or operating as small entities, and they face the challenge of meeting stakeholders' needs with limited resources. Furthermore, these institutes often need support for European integration, including those from existing EU members (e.g., those from EU-13 or EU-25 countries) or are from countries undergoing the accession process to the EU. The capacities developed will help support free movement of goods, environment protection, health protection of citizens, consumer protection, among other aspects. In addition to supporting those NMIs and DIs with emerging metrology systems or in emerging fields of measurement, there is a demand for specific knowledge across the whole EURAMET landscape e.g., related to international quality infrastructure, the CIPM MRA, operation of a Technical Committee or piloting an interlaboratory comparison.

Objectives

The overall objective of this coordination project is to assist EURAMET's bodies to achieve impact for the European metrology community by coordinating and managing the capacity building instruments used for and aligned with EURAMET's Capacity Building Strategy.

The specific objectives are:

1. To implement a Researcher mobility support (RMS) capacity building instrument to develop or reinforce EURAMET member NMI/DI research capability, and to award and manage at least 25 RMS during the project implementation period.
2. To implement a Mentoring Scheme Awards (MSA) capacity building instrument to support and enable the integration and active participation of all EURAMET members into EURAMET structures, and to award and manage at least 25 MSAs during the project implementation period.
3. To support building the human and institutional capacity of member NMIs and DIs necessary to respond to the demands of indirect stakeholders by the organisation of and support for at least 25

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

training events (courses, workshops and summer schools) during the project implementation period. The topics of these courses and materials to be defined following stakeholder consultation.

4. To facilitate the take up of the capacity building instruments implemented by the project by end users (in particular EURAMET NMIs/DIs), and to maximise the impact and benefits obtained from these instruments.

Methodology and results

The project will manage and implement 3 capacity building (CB) instruments, namely Researcher Mobility Support (RMS), Mentoring Scheme Award (MSA), and Training events (courses, workshops and summer schools). The RMS supports researchers from EURAMET NMIs and DIs to join an organisation in a different country to their employer for between one to nine months, in order to perform research in the selected metrology related field. The MSA provides a platform for staff from two different metrological institutes (EURAMET NMI or DI), in different countries, to set up a partnership and work together on a relevant topic, such as technical, managerial, comparisons or traceability.

All necessary documents and procedures for running the calls for the RMS, the MSA and the training events, the application process, the evaluation process, and the monitoring process will be developed and made available. This will include establishing a transparent process describing clear rules and eligibility criteria for the various instruments and the applicants, how to conduct the evaluation procedure, including roles of the evaluation panel, and defining the reporting and financial support mechanisms. In addition, a web-based platform will be developed for easy and targeted access for stakeholders to obtain relevant information concerning all the CB instruments, e.g., call documents, call schedule / deadlines etc, and the web platform will allow submission of proposals / applications.

The consortium will seek advice from EURAMET's Bodies and the project's Stakeholder Committee (embracing representatives of bodies involved in Capacity Building) in order to identify specific needs for training events (courses, workshops and summer schools) and will prioritise the proposed topics.

Calls for all instruments will be announced on a dedicated web platform. After passing eligibility requirements, the proposals will be evaluated by the Stakeholder committee in line with the objectives and envisaged impact with a go/no go conclusion. Once applicants have been informed of the outcome of the evaluation and the contractual process has been completed for successful applications, the coordinator will distribute funds to participants/hosts of the activities, either through the cascade funding (financial support to third parties) mechanism or through reimbursement of costs. Information about the activities performed will be available at the project web platform and further news and articles will be prepared e.g., for the EURAMET and BIPM web pages, and social media. EURAMET bodies, such as the BoD WGCB, will also be briefed. Recipients of capacity building funding will collect and submit case studies or news stories to CMI for review and capturing the impact of CB instruments.

Outcomes and impact

Outcomes for user communities

The early project outcomes will be with the National Metrology Institutes and Designated Institutes of EURAMET. They will benefit from training courses, workshops, summers schools, research mobility support and mentoring scheme awards by:

- Building the human and institutional capacities (as technical or managerial knowledge related to measurement techniques, CIPM MRA or operation of an institute, research project management, administration and reporting);
- Implementing new measurement techniques or calibration or verification procedures;
- Establishing new calibration and measurement services;
- Starting activities needed for international recognition of particular calibration and measurement services;
- Starting activities needed to foster integration in CIPM MRA processes and mechanisms plus integration into EURAMET structures and activities (e.g., participation in a TC or EMN, participation

and piloting a international comparison, taking on the TC chair position, evaluation of a comparison, evaluation of a CMC claim);

- Starting/fostering research in particular field;
- Improving an NMI's/DI's capabilities needed to address the current and emerging needs of stakeholders e.g. calibration laboratories and conformity assessment bodies, industry, legal metrology, healthcare services, environmental protection agencies, regulatory bodies, including consumer protection, national quality infrastructure bodies and academia;
- Improvement of the NMI/DI management;
- Widening employers' professional networks which will enable future collaboration in various forms.
- Preparing and presenting scientific papers and posters (e.g. at workshops, conferences);

Wider, longer-term economic, social, and environmental impacts

The NMIs and DIs will benefit as direct user of project activities. Having sustainable metrological capacity building on a European level with long term planning will benefit all European NMIs and DIs because they will be able to coordinate and optimise their resources (both time and money) for that and plan staff training on the long term. Coordinated capacity building will save resources for all NMIs and the final effect will be much higher e.g., a summer school on a specific topic, with concentrated knowledge transfer from peer European experts covering a complete portfolio from that field.

The international metrology community will benefit both from the establishment of the equivalence of measurements and from the fact that more NMIs and DIs will be able to take on CIPM MRA tasks, which will distribute the workload between NMIs and DIs (e.g., piloting international comparisons, review of CMCs, hosting the CB activities).

Wider impact will be through the support provided to NMIs' and DIs' customers and stakeholders. NMIs and DIs will be able to provide the metrological services needed by industry, pharmaceuticals, food production, the energy sector as well as secondary calibration laboratories and various conformity assessment bodies (e.g., laboratories for legal metrology, health, environmental and consumer protection).

The availability of internationally comparable and recognised measurements results for many areas will have a Europe wide impact. The wider benefits include (i) new internationally recognised services of calibration laboratories and conformity assessment bodies, (ii) reducing barriers for trade (through recognition of the national quality infrastructures of the countries involved), (iii) supporting widening countries in their accession to EU, (iv) improved reliability and international recognition of national (health protection agencies and environment protection agencies, (v) strengthening of local bodies, e.g. national consumer protection agencies thus providing benefit to local consumers, and (vi) supporting European competitiveness in metrological areas which will help meet overall aims as smart concepts, environmental goals etc.

Project activities will be regularly communicated and disseminated via the project web page, the EURAMET and BIPM web pages, and possibly social media (e.g., LinkedIn, Instagram, Facebook). At least 2 case studies and success stories will be prepared based on project outcomes.

In the long term the project will help support a wide range of European aims, e.g. Including industry, circular economy, waste reduction directive, and energy directives.

Project start date and duration:		1 June 2024, 48 months
Coordinator: Peter Kiska Organisation: Cesky Metrologicky Institut Tel: +420 725 557352 E-mail: pkiska@cmi.cz Project website address: n/a yet		
Internal Beneficiaries: 1. CMI, Czechia	External Beneficiaries: -	Unfunded Beneficiaries: -



Publishable Summary for 23FUN01 PhoQuS-T Photonic and quantum sensors for practical integrated primary thermometry

Overview

Temperature is one of the most frequently and widely used measurements and it influences almost every physical, chemical, and biological process. This project aims to take advantage of the kelvin redefinition by developing novel small-scale optical based primary thermometry approaches for the dissemination of thermodynamic temperature to industries such as semiconductor, micro- and nanotechnology, aerospace and naval, green energy and quantum technologies. It will significantly progress the state of the art by a) combining complementary photonic thermometry techniques (quantum opto-mechanics, optical phase noise, and photothermal effect) for the first time, b) investigating several sensor geometries (1D, 2D) and materials (e.g., Si, SiN, GaP, InP) of micro- and nano-sensing structures and c) extending the operating temperature range from 4 K to 500 K. In addition, the project will demonstrate practical quantum applications of the developed temperature sensors for ion trap monitoring and in quantum-based pressure standard.

Need

The kelvin redefinition has stimulated new and disruptive approaches to delivering temperature traceability, namely practical primary thermometry at the point of measurement. Such approaches better meet user needs by providing lifetime on-demand reliable traceable temperatures. The most innovative ways to provide such traceability are the photonic/quantum-based approaches investigated in this project. Whilst in their infancy these approaches have the potential to radically change the practice of thermometry through provision of in situ traceability without the need for sensor removal for recalibration (thanks to the high chipset integration capacity and the possibility of a “self-calibration”). Beside purely “metrological” need for a practical primary wide-range thermometer for the realisation and dissemination of the thermodynamic temperature according to the *mise-en-pratique* for the definition of the kelvin, multiple users would benefit from such an approach: from quantum technologies community to cryogenics, photonic/semiconductor, aerospace, transportation and energy (hydrogen) sectors. The sensors developed in this project are adapted to these applications where usual temperature sensors are unsuitable: self-calibrated optomechanical resonators as well as photonic resonators could provide robust, small-scale and wide-temperature range sensors, immune to electrical noise and easy to integrate.

This project will develop integrated optical practical primary thermometry from 4 K to 500 K to enable in-situ traceability in further practical applications. This will be reached through a combination of different technical approaches. With the optomechanical sensors (1D (nanobeam) or 2D (membrane)) the optical noise thermometry will be developed from 4 K to 300 K and the quantum thermometry will be tested below 10 K in order to provide a quantum reference for the optical noise thermometry (Objective 1). The operating temperature range will be extended from 80 K to 500 K with high-resolution photonic sensors based on passive and novel active photonic integrated circuits of micro- and nano-resonators. These photonic chip-based sensors need to be designed, manufactured and characterised and enhanced read-out techniques need to be developed and tested (Objective 2). For further practical applications, the integrated packaging for optomechanical and photonic sensors need to be developed as well as robust fibre to chip coupling over the temperature range from 4 K to 500 K needs to be developed by investigating different technologies for direct fibre coupling (laser welding, gluing, mechanical support) (Objective 3). Finally, the developed sensors need to be metrologically evaluated by establishing the corresponding uncertainty budgets for optomechanical and

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: September 2024

photonic sensors in their respective operating ranges and their application in ion trap monitoring and quantum-based pressure standard will be demonstrated (Objective 4).

Objectives

The overall objective of the project is to develop integrated optical practical primary thermometry with a combination of different approaches: with the optomechanical sensor, the quantum thermometry below 10 K will provide a quantum reference for the optical noise thermometry (operating in the range 4 K to 300 K), whilst using the high resolution photonic (ring-resonator) sensor the temperature range will be extended from 80 K to 500 K.

The specific objectives of the project are:

1. To develop optical noise thermometry from 4 K to 300 K with a target temperature uncertainty of 0.1 K, by using 1D (nanobeam) or 2D (membrane) optomechanical sensors and to test quantum thermometry below 10 K, in order to provide a quantum reference for noise thermometry. In addition, to design, fabricate and characterise sensors using different mathematical models. (WP1)
2. To extend the range for photonic thermometry from 80 K to 500 K, based on passive and novel active photonic integrated circuits of micro- and nano-resonators. To design, simulate, manufacture, and characterise (thermally and optically) the unpackaged photonic chip-based sensors, with a target Q factor of 10^7 . In addition, to develop and test enhanced read-out techniques, including reliable experimental set-ups and theoretical modelling. (WP2)
3. To develop integrated packaging (below cm^3) for optomechanical and photonic sensors and to develop robust fibre to chip coupling over the temperature range from 4 K to 500 K by investigating different technologies for direct fibre coupling (laser welding, gluing, mechanical support) to minimise the optical loss and achieve negligible strain effects over this temperature range. (WP3)
4. To validate the fabricated primary optomechanical sensors from Objective 1 and to calibrate the interpolating sensors from Objective 1 and 2 traceable to the international temperature scale (ITS-90). Then to evaluate the corresponding uncertainty budgets for optomechanical and photonic sensors in their respective operating ranges (target uncertainties for optomechanical sensors are 0.1 K from 4 K to 300 K and for passive photonic sensors are 25 mK from 80 K to 500 K and 5 mK from 283 K to 363 K.) In addition, to demonstrate the application of the calibrated photonic sensors in relevant quantum applications, such as in ion trap monitoring and quantum-based pressure standard. (WP4)
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (photonic and optomechanical temperature sensors, accredited laboratories, instrument manufacturers), research organisations, standards developing organisations (CIPM Consultative Committee for Thermometry (CCT), EURAMET and other RMO TC-Ts) and end users (academia, national metrology institutes, industrial R&D laboratories. (WP5)

Progress beyond the state of the art and results

This project aims at a paradigm shift in temperature measurement not only by producing a practical primary thermometer (in-situ traceability at point of measurement), but also by adopting a photon-based approach with a sub- μm scale spatial resolution.

Within this ambitious objective, significant advance will be made building on the achievements of the EMPIR JRP 17FUN05 PhotOQuanT, where the state-of-the-art optomechanical and photonic resonators were fabricated demonstrating optomechanical noise thermometry (at cryogenic temperatures) and photonic thermometry (around room temperature). State of the art will be advanced through using integrating photonic technologies which will combine different techniques onto a single device for a first practical quantum primary thermometer from cryogenics to 500 K. Quantum thermometry will provide a quantum reference for the optical noise thermometry operating in 4 - 300 K range, while sub mK resolution and wide operational range to 500 K are provided through photonic thermometry. In this project, for the first time such a practical primary temperature sensor will be developed, validated and its quantum applications demonstrated. For this breakthrough, all scientific/technical work in the JRP requires significant progress beyond state of the art.

Objective 1: Development of optical noise thermometry from 4 K to 300 K and quantum thermometry below 10 K

In the EMPIR JRP 17FUN05 PhotOQuanT, optomechanical noise thermometry was demonstrated over 4 - 300 K with 1D-structures suffering from self-heating. New 1D/2D geometries (to reduce the self-heating by a factor of 10) and arrays of resonators (to reduce uncertainty over a large temperature range) will be developed.

Quantum correlation thermometry facilitates integrated, nanoscale, magnetic-field insensitive primary thermometry as demonstrated at NIST (2017). Here, advantage will be taken of this technique at cryogenic temperatures (below 10 K) to provide a quantum reference for a high-performance noise thermometry on the same optomechanical structure operating in 4 - 300 K range (with target uncertainty 0.1 K).

Objective 2: Advanced photonic thermometry from 80 K to 500 K

Photonic thermometry is based on the thermo-optic effect and offers very high sensitivity (70 pm/K) and sub mK resolution (shown in EMPIR JRP 17FUN05 PhotOQuanT project). This project will go beyond the state of art, firstly, by exploring enhanced read-out techniques and by improving the device design to extend the operation range (80 K - 500 K) exploring Si and SiN; and secondly, by developing a non-Si based novel active thermometry approach (combining laser source and photonic sensor) as a step towards the fully integrated device.

Objective 3: Robust fibre to chip coupling packaging solutions over 4 - 500 K temperature range

The free-space coupling drastically limits the practical application of the optical sensors. This project will go beyond the state of the art by developing different approaches (gluing, welding, mechanical) for packaging and robust fibre-to-chip coupling over a large temperature range (4 K - 500 K) to mitigate for thermal expansion mismatch between fibre, chip and adhesive material over temperature range while catering to the requirements of optomechanical and photonic sensors.

Objective 4: Metrological validation and applications

Photonic thermometry and optomechanical thermometry are both recent emerging technologies. Nowadays, NIST demonstrated a proof of principle of the quantum correlation technique to calibrate thermal noise versus quantum noise in an optomechanical resonator. The first results of EMPIR JRP 17FUN05 PhotOQuanT project on optomechanical noise thermometry were mainly limited by a strong self-heating effect and the photonic thermometry has been demonstrated around room temperature with a standard deviation about 10 mK. Recently, uncertainties of 10 mK could be demonstrated by the Canadian NMI. The progress introduced in this project (2D optomechanical resonator with self-heating divided by at least 10, advanced photonic resonators enabling a broad temperature range, from 80 K to 500 K) should allow the consortium to improve the state of the art with these emerging technologies. Within this project, the metrological validation will be performed establishing traceability to ITS-90 over their full temperature range together with computation of the respective uncertainty budgets (with target uncertainties for optomechanical sensors of 0.1 K from 4 K to 300 K and for passive photonic sensors of 25 mK from 80 K to 500 K and 5 mK from 283 K to 363 K).

In addition, in this project, the application of these sensors to measure the temperature drift of ion traps, without interference with their operation will be explored. The application of the photonic thermometry for the temperature assignment in the photon-based approach for pressure measurements will open the way towards an all-optical quantum-based pressure standard.

Outcomes and impact

This research project focuses on the development of integrated optically based practical primary thermometry from 4 K to 500 K standard.

Outcomes for industrial and other user communities

The lack of practical primary thermometers constitutes a barrier for the dissemination of the redefined kelvin by the mise-en-pratique for the definition of the kelvin (MeP-K-19) i.e. for addressing industry issues. As a result, the practical primary thermometers developed here are expected to have high impact in industry.

This project will provide a technological breakthrough for integrated circuit temperature sensing issues, and also for other related temperature measurement needs e.g. those requiring reliable in-situ long time scale measurements such as space, aircraft, submarine or naval, where sensor retrieval (and hence recalibration)

is not feasible. Also, the wide-range primary sensor developed in this project, covering the cryogenic temperature range, is of particular interest for rapidly growing sectors such as Hydrogen (liquid H₂ storage) and Quantum Technologies, where temperature-controlled cryostats is crucial. The use of the new sensors developed in this project will enable accurate, zero drift, temperature sensing in the extended operating range (4 K to 500 K) having the capability to be embedded into a chipset or other integrated technologies – a technological breakthrough.

Outcomes for the metrology and scientific communities

The recommendations of the Consultative Committee for Thermometry (CCT) for the mise-en-pratique for the definition of the kelvin (MeP-K-19), specifies that a primary thermometry method must fulfil particular criteria in order to be endorsed for provision of temperature traceability. This project targets these requirements and aims to develop the first on chip practical primary thermometer from 4 K to 500 K, the impact of this on practical primary thermometry practice is potentially very high as the practical optical thermometers developed will open the way to a new metrology traceability scheme, which will have to be agreed by the international metrology community.

In addition to the benefits to the temperature metrology community from this project's outputs, the wider scientific community will be able to take advantage of the new sensors (e.g lab-on-a-chip application or in-situ measurement at the sub- μ m scale) and will benefit from the technological developments (e.g. robust coupling fibre-chip, integrated optical components) associated with the large operational temperature range.

Outcomes for relevant standards

The practical primary thermometry approach developed will provide a new and more straightforward way to deliver SI traceability direct to where the user needs it most at the point of application. This is a paradigm shift in the way traceability is delivered (currently through an unbroken chain of measurements) and will require validation from the CCT to be accepted and will require some form of a standardisation recommendation before full implementation can be realised. More generally, and within a shorter timeframe, this project will produce technical data and documents for the CCT, via close cooperation with its working groups and task groups.

The relevant committees will be kept informed of the progress and outcomes of the project: annual reports to the CCT and RMO TC-Ts. The project consortium will raise awareness of these developments, concerning the quantum sensors and their needs for standardisation, within CEN-CLC Joint Technical Committee 22 "Quantum Technologies".

Longer-term economic, social and environmental impacts

Temperature is probably the most frequently and widely used measurement, and it influences almost every physical, chemical, and biological process. Consequently, any change to the fundamentals of thermometry, its measurement and traceability will have far-reaching impacts in all areas of human endeavour.

A practical primary thermometer available at the point of use introduces a paradigm change in the traceability scheme to the kelvin: calibration against standards held by a national metrology standard may no longer be required. A simple stable in-situ temperature reference is sufficient to estimate the statistical component of the uncertainty of the primary thermometer. This significantly reduces the complexity of the traceability process as well as its cost. Industry will be more efficient and productive as thermometers will no longer require calibration meaning that optimum energy is used, minimising emissions and waste.

The research will have a significant impact at the European level because it enhances the European laboratory network for quantum and nano-scaled temperature metrology (established during EMPIR JRP 17FUN05 PhotOQuant) and opens new opportunities for the first commercialisation of photonic temperature sensors in Europe. Many industries such as semiconductor, micro- and nanotechnology, aerospace and naval, green energy and quantum technologies, will benefit from the project's output and this should strengthen European industrial infrastructure for the development of new services and products. The project will improve collaboration between European NMIs, academia and technological institutions enabling the EU to take a leading role in the future in this important emerging technology area.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2024, 36 months
Coordinator: Olga Kozlova, LNE Tel: +33(0)158808901 E-mail: olga.kozlova@lne.fr Project website address: https://phoqus-t.com/		
Internal Beneficiaries: 1. LNE, France 2. CEM, Spain 3. CNAM, France 4. INRIM, Italy 5. PTB, Germany 6. RISE, Sweden 7. VTT, Finland	External Beneficiaries: 8. CNRS, France 9. IHP GmbH, Germany 10. LUH, Germany 11. SU, France 12. TU Delft, Netherlands 13. TUB, Germany	Unfunded Beneficiaries:
Associated Partners: 15. NPL, United Kingdom 16. UofG, United Kingdom		
Affiliated Entities: 14. UPCite, France (affiliated CNRS)		



Publishable Summary for 23FUN02 CoCoRICO

Controlled confinement to reduce the inaccuracy of clocks based on optical lattices

Overview

Quantum technologies is a fast developing scientific and industrial domain with an expected multi-billion Euro market of technological solutions for industries and citizens. It comprises the field of quantum sensing, in which optical lattice clocks (OLCs) are one of the most precise measurement instruments, and quantum computing and simulation, which require the controlled manipulation of quantum objects such as trapped ultra-cold atoms. This project aims at bringing together the fundamental technologies used in these two domains by developing tailored and controllable potentials for lattice clocks, such as high order modes, tweezers, or conveyor belts, potentials able to take advantage of quantum entanglement, and in order to use them to explore and better evaluate the systematic uncertainty of these clocks.

Need

The EURAMET European Metrology Network for Quantum Technologies (EMN-Q) has formulated a strategic research agenda highlighting the need to develop quantum sensors, and in particular optical clocks, to improve the measurement capability of time and frequency, but also for field applications of these sensors, such as geodetic measurements.

In parallel, the upcoming redefinition of the SI second with optical clocks, sets immediate goals for the developments of these clocks: a clear understanding of their ultimate capabilities is required to make the most enlightened choice for the new definition. At the same time, proving the robustness and reproducibility of the accuracy budget of optical clocks, appears as a necessity in the current context, where only seldom effective comparisons of independent clocks approach the best published systematic evaluations.

In the quantum physics community, the individual manipulation of cold atoms has seen a recent surge of interest, driven by new capabilities to trap atoms in controllable potential, with a clear application in quantum computing and simulation. Techniques from frequency metrology also percolate in this community, as ultra-stable lasers, to probe narrow transitions, have become readily available industrial products. In this project these techniques will be applied for the development of optical lattice clocks, in order to establish new methods to estimate systematic effects, to verify the robustness of their evaluation, and to offer new possibilities for the accuracy of optical lattice clocks.

Objectives

The overall objective is to explore the fundamental limits of the accuracy of OLCs by implementing innovating trapping strategy, to exploit the variability in these trapping strategies, to validate the systematic evaluation of OLCs, and to confront systematic evaluation in different European NMIs by clock comparison through optical fibre links.

The specific project objectives are:

1. To study the systematic effects associated with lattice light-shifts and cold collisions by developing tailored dipole trapping potentials for OLC. In addition, to determine how to mitigate lattice-induced decoherence in shallow lattices, and to mitigate the collision effects that currently limit the use of bosonic isotopes. OLC configurations will include high order transverse Gaussian beams and patterned or

Report Status:
PU – Public, fully open

Publishable Summary

Issued: July 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



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painted potentials. Sub- 10^{-18} comparisons of lattice light shifts and cold collision shifts (for 10^4 to 10^5 atoms) will also be assessed with these configurations.

2. To demonstrate engineered or movable potentials, for dead-time free clocks and active clocks, using novel techniques (e.g. cold atoms in optical tweezers, hollow core fibres, continuous loading of cold atoms, conveyor belt potentials). Then by using this ability, to control and modify the OLC trap geometry, (i) to explore cold collision effects, and (ii) develop methods for the continuous flux of atoms.
3. To demonstrate fast and low-noise readout of hybrid cavity OLCs in environments where strong light-matter interaction is overlapped with the optical lattice. In addition, to study the effects at fractional resolutions of 10^{-18} or lower, associated with synthetic interactions and entangled states.
4. To determine the effect of background gas collisions with atoms trapped in dipole traps at fractional resolutions of 10^{-18} : This will include (i) the measurement of the atom trapping lifetime and frequency shift using clock comparisons, (ii) the controlled insertion of background gas pressure; and (iii) comparison with theoretical models, i.e. from semi-classical approaches to quantum approaches including the anisotropy of collisions.
5. To demonstrate the improved accuracy of OLCs gained from Objectives 1-4 using agile optical fibre link comparisons between European metrology institutes. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, research organisations (EMN Quantum), standards developing organisations (BIPM Consultative Committee for Time and Frequency (CCTF), EURAMET TC-TF) and end users (time and frequency, fundamental physics and geodesy sectors).

Progress beyond the state of the art and results

Objective 1: Study of systematic effects associated with lattice light-shifts and cold collisions by developing tailored dipole trapping potentials for OLC

Several groups have developed tailored potential for cold atoms, such as arrays of optical tweezers exhibiting long coherence time on clock transition, with the perspective of the individual control of atoms, or tailored transverse mode of dipole potentials with SLMs.

In this project, such methods for trapping and probing of cold atoms will be demonstrated in state-of-the-art optical lattice clock systems, with tailored dipole trap (high order transverse modes, and reconfigurable optical tweezers), fed by high-flux atomic sources. This will be used to characterise in a robust way several prominent systematic effects of optical lattice clocks below 10^{-18} , such as static EM fields, trap-induced light-shifts, and inter-atomic interactions.

Objective 2: Engineered or movable potentials for dead-time free clocks and active clocks

Movable potentials enable the transfer of ultracold atoms from a magneto-optical trap (MOT) source to one or more interrogation zones with well controlled environment. Transfers have been demonstrated from a MOT to a single, black-body shielded interrogation zone and from a MOT to a multiple, unshielded regions using movable optical lattices. More recently, a moving optical lattice was also proposed as a base for the longitudinal Ramsey spectroscopy of atoms enabling continuous probing of the clock transition/

The continuous transport atoms into shielded environments will be demonstrated in this project, enabling zero-deadtime operation. Systematic shifts influenced by the transport (in particular shifts from sample density and temperature, but also shifts from residual transport beam stray light) will be characterised, and potential applications of trapping the atoms in moving lattices inside hollow-core photonic fibres as a source for continuous reloading of ultracold strontium atoms into an active superradiant optical atomic clock will be checked.

Objective 3: Fast and low-noise readout of hybrid cavity OLCs in environments where strong light-matter interaction is overlapped with the optical lattice

The hybrid atom-cavity system experienced a surge in interest and development towards its application on optical lattice clocks. Several milestones have been achieved in recent years, including the demonstration of non-destructive read-out of the transition probability in OLCs (EMRP JRP EXL01 QESOCAS), the first demonstration of entanglement-enhanced stability and the first realisation of spin-squeezed clocks at a measurement precision level of 10^{-17} (EMPIR JRP 17FUN03 USOQS).

Atom-cavity effects will be studied in this project with fractional resolutions of 10^{-18} in strongly coupled light-matter systems, and pursue approaches evading the measurement problem, which are enabled by driven-dissipative cavity-mediated interactions to generate metrologically-useful entanglement. This work will be built on techniques and methods initiated by the EMRP JRP EXL01 QESOCAS and EMPIR JRP 17FUN03 USOQS JRPs.

Objective 4: Study of background gas collisions effect with atoms trapped in dipole traps at fractional resolutions of 10^{-18}

The correction of frequency shifts caused by background gas collisions for OLCs is currently based either on a semi-classical model describing the quantum scattering that was developed for microwave fountain clocks, but without any reproduction by independent laboratories or strong confirmation that those measurements were fully dominated by H_2 . These data are sufficient to reach an accuracy on the order of 10^{-18} for systems dominated by H_2 and with a sufficiently large lifetime (several seconds).

In this project, the measurement of the frequency shift will be improved and independently reproduced as induced by background gas collisions for cold Sr and Hg atoms for a variety of background gasses. This will allow to control this up to now little understood systematic effect below 10^{-18} level, even for moderate lifetimes. These measurements will be backed by theoretical and numerical models.

Objective 5: Improved accuracy of OLCs using agile optical fibre link clock comparisons between European metrology institutes

Phase compensated optical fibre links allow for the high resolution of optical clocks throughout Europe, with a systematic and statistical uncertainty at least below 10^{-19} . Large comparison campaigns have been conducted (EMPIR JRP 18SIB05 ROCIT, EMPIR JRP 15SIB03 OC18). However, large comparisons campaigns involving a dozen of optical clocks require a heavy planning and preparation of the clock, that is not compatible with involving new or experimental configurations as the ones proposed in this project.

In this project, the outcomes of Objectives 1-4 will be backed by local and remote clock comparisons with tailored and engineered potentials. For remote comparisons, operational optical fibre links will be exploited across Europe in agile comparisons, developed and characterised by previous projects (EMPIR JRP 15SIB05 OFTEN, EMRP JRP SIB02 NEAT-FT). Several of these comparisons will provide data for International Atomic Time (TAI) calibrations.

Outcomes and impact

Outcomes for industrial and other user communities

Optical lattice clocks are starting to gain industrial uptake, after two decades of academic development, and the maturity of the laser technologies required to operate them. This uptake is motivated by emerging field applications such as geodesy or optical time scales, and by the dominant position of optical lattice clocks for the next definition of the second. In Japan, compact transportable Sr clocks will soon reach the market; in Europe, the AQuRA project (No101080166 EU Horizon Europe RI programme) consortium is currently building a prototype for an industrial grade transportable Sr clock. The AQuRA consortium comprises several leading European companies in laser technologies and quantum sensors, together with several academic participants of the CoCoRICO project who will be sharing their expertise in optical lattice clocks. The AQuRA project, industrial stakeholders and end-users aiming at developing field deployable clocks (such as in the field of geodesy (characterisation of the Earth gravitational potential with accurate clocks with improved accuracy) and the generation of optical time scales (replacing microwave time scales with the advent of a new definition of the SI second)). These groups will directly benefit from the knowledge and expertise acquired during the CoCoRICO project which will allow the development of more accurate clocks (e.g. with reduced background gas collision uncertainty) and new trapping configuration (e.g. dead time free clock based on conveyor belt to avoid bulky laser stabilisation). To ensure this, the project participants will organise a joint workshop with the AQuRA project, as well as workshops for stakeholders to disseminate the project results to support the implementation of novel trapping strategies developed in this project to industrial groups and end-users.

In addition, the spectral purity of the trapping laser is a critical characteristic for the accuracy of optical lattice clocks. The participant has developed calibration methods to evaluate the suitability of various trapping laser sources for high accuracy OLCs. This project will reinforce this capacity through building up the acquired knowledge about lattice light shift systematic effects. This is of particular interest for manufacturer of transportable OLCs systems, or spatial clocks such as ESA, who has already shown interest in this topic in the past.

Outcomes for the metrology and scientific communities

The outcomes of this project will have a direct impact on the time and frequency metrology community, by advancing the knowledge about OLCs, their characterisation techniques, and by producing comparison data of clock frequency ratios. These outcomes will also directly contribute to the fulfilment of the roadmap towards the redefinition of the SI second. Specifically, the project participants will publish guidelines and papers on the developed new methods for improving the accuracy of OLCs, which will provide the community with new data for correcting for systematic effects, such as background gas collisions. In addition, clock comparison data will be published, and TAI calibration contributed to the BIPM.

The outcomes of the project (guidelines and papers about the development of new confinement strategies) will also be of interest to the broader quantum technology community, in which these techniques are used to manipulate and address individual atoms, sometimes using the narrow resonances originally studied for time and frequency metrology.

Finally, the data sets produced by optical clock comparisons will provide material for improved tests of fundamental physics, including the search for variations of fundamental constants and the search for dark matter.

Outcomes for relevant standards

This project targets two specific standard committees:

The Working Groups of the CCTF and CCL are involved in monitoring and exploiting the progress of optical clock technologies, and in validating the criteria fulfilment of optical clocks before the redefinition of the SI second. The new systematic evaluation of OLCs performed in this project, the clock comparisons to validate this systematic evaluation and reduce new frequency ratio measurements and TAI calibrations, are therefore of high interest for these WGs. The project participants are often members of these working groups, or in close collaboration with them, and will benefit from this experience to promote the project outcomes to the relevant WG. To this aim, they will send reporting notes in preparation for the WG meetings.

Furthermore, the EURAMET European Metrology Network (EMN) for Quantum Technologies provides active coordination of European measurement science research to maintain competitiveness in the field of quantum technologies. Optical lattice clocks, as quantum sensors, are key tools in this field. The objectives of this project, especially on tailored and reconfigurable potentials (Objective 1) and hybrid cavity systems able to generate entanglement (Objective 2), are particularly relevant to the EMN-Q, and the associated project outcomes will be reported to this committee. The participants will present the project outcomes at the general assembly of the EMN-Q.

Longer-term economic, social and environmental impacts

According to the Key Performance Indicators of the European Quantum Flagship, a 150 % growth of market uptake of quantum technologies is expected by the end of the decade. This project, and the close relation between its participants and the relevant companies, is expected to directly contribute to this growth in the domain of quantum sensing. Furthermore, this project is relevant to the quantum computing and simulation domains, through the trapping and probing that the project participants will develop, and which are applicable to controlling and manipulating individual quantum systems. These domains, although not as mature today, are expected to have similar market uptake by 2030.

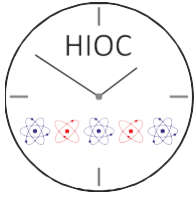
In environmental impact, and in specific in geodesy, the availability of high performance, repeatable and inter-connected optical frequency standards will allow geophysicists to monitor, with unprecedented accuracy, mass redistribution processes within the Earth. This will be possible through an improved system of vertical references at continental scales, which are currently unreachable by smooth satellite data or local gravity measurements. The applications of such improved vertical references range from seismic modelling, prediction of volcanic eruptions, to real time ground water and sea level monitoring. In addition, such data provides critical input into models used to study and forecast the effects of climate change.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2024, 36 months
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Project website address: http://cocorico.obspm.fr		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. OBSPARIS, France	4. CNRS, France	-
2. INRIM, Italy	5. IOTA, France	
3. PTB, Germany	6. UMK, Poland	
	7. UvA NL, Netherlands	
Associated Partners: 8. NPL, United Kingdom 9. UDUR, United Kingdom		



Publishable Summary for 23FUN03 HIOC High-accuracy ion-based optical clocks

Overview

To date, the smallest systematic uncertainty of an optical clock has been reported for a clock that uses the reference transition of a single trapped ion. However, whilst single ions can provide the highest level of accuracy, it requires weeks of averaging to reduce the statistical uncertainty to below 10^{-18} . As this is a direct result of the quantum nature of the reference system, much faster averaging is expected when using more ions and reference transitions with higher f frequencies. In this project experimental techniques will be used to realise such ion-based optical clocks using multiple ions or transitions with higher f frequencies and ensure they have the highest level of accuracy and stability. Such optical clocks will be developed, and their performance will then be demonstrated by comparisons.

Need

The characteristic microwave or optical f frequencies used in current atomic clocks produce the most precise measurement devices available today. Within the SI system of units, the realisation of the unit of time with Caesium atomic clocks plays an essential role, as the unit second is contained in the definition of 6 of the 7 base units via their defining constants. Therefore, having highly accurate, stable and reliable reference f frequency standards is a pre-requisite not only for the SI System of Units but also for many everyday technologies that rely on precise time keeping such as banking transactions, communication and navigation.

Due to their higher reference transition f frequency, high-accuracy optical clocks have made great progress with a variety of different reference systems based on neutral atoms and single ions. The highest accuracy has so far been obtained for optical clocks with single trapped ions. However, a clock with a single ion requires weeks long averaging time to reduce the statistical uncertainty in measurements. To overcome this limitation, ion-based optical clocks using multiple ions or transitions with higher f frequencies need to be developed, evaluated, and tested for use as future primary standards of time and f frequency. This is particularly urgent given the growing needs in global communication and navigation.

For such optical clocks using multiple ions or transitions with higher f frequencies, methodologies such as trapping and cooling of large ensembles of ions (Objective 1) and optimal interrogation strategies for improving the frequency stability (Objective 2) need to be developed. These clocks with higher stability need to provide the same or even superior accuracy compared to single ion optical clocks and their performance needs to be validated in comparisons (Objective 3). Alongside the use of established optical reference transitions, transitions with higher f frequencies and greater immunity to the perturbing fields are of particular interest. For this, the low-energy nuclear transition in Thorium (^{229}Th) and transitions in highly charged ions (HCI) need to be investigated (Objective 4).

Objectives

The overall goal of this project is to develop high-accuracy ion-based optical clocks using multiple ions or transitions with higher f frequencies as future primary standards of time and f frequency and to validate them with comparisons.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: May 2024

1. To develop improved methods for trapping and cooling large ensembles of ions, for use in advanced ion-based optical clocks. This will include the study of (i) ion traps with ultra-low heating rates, (ii) the use of superconducting materials at cryogenic temperatures for shielding of electromagnetic fields, (iii) the confinement of ions in engineered static electric and optical fields, (iv) narrow atomic transitions for fast motional ground-state cooling and (v) the minimum temperature rise of the ion crystal during state detection.
2. To increase the frequency stability of ion-based optical clocks by a minimum of factor of 2 by simultaneously interrogating 4 or more ions. This will include an assessment of technical noise sources so that the maximum number of quantum absorbers can be used. In addition, the use of (i) quantum control techniques, (ii) entanglement and (iii) spin squeezing, to increase ion-based optical clock performance, will be investigated.
3. To develop multi-ion based optical clocks with uncertainties below 10^{-18} and to verify their performance via interspecies clock comparisons. In addition, to assess their frequency shifts resulting from (i) external electric fields, (ii) magnetic fields including thermal radiation, (iii) collisions between the trapped ions and background gas molecules.
4. To develop improved and reliable techniques for optical clocks, using novel reference transitions of HCl and ^{229}Th nucleus, in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) ranges. This will require the development of dedicated laser sources, their integration with the ion trap system and the traceability of their output frequency.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, research organisations (European Quantum Technology Flagship, EMN Quantum), standards developing organisations (BIPM CCTF, EURAMET TC-TF) and end users (in the time and frequency and optical sectors).

Progress beyond the state of the art and results

This project builds upon the achievements of previous EMPIR and Partnership projects, most recently 17FUN07 CC4C, 20FUN01 TSCAC and 22IEM01 TOCK. Fundamental techniques such as trapping and cooling pairs of different species for clock applications have been investigated in 17FUN07 CC4C, and within 20FUN01 TSCAC the benefit from the use of a co-trapped atomic species in clock operation has been demonstrated. Furthermore, 20FUN01 TSCAC has successfully provided the first demonstration of an optical clock based on a reference transition of a highly charged ion at an optical wavelength. Within this project the use of different ion species shall be continued, and the combined interrogation of larger numbers of ions shall be used to reduce the statistical uncertainty. Such multi-ion optical clocks will be evaluated with a focus on the traceable measurement and their performance will be verified in comparisons. Here this project will benefit from the development of robust components and the complete transportable atomic clocks that are being developed and used within 22IEM01 TOCK. While the focus in this project is on demonstrating ultimate accuracy and performing local clock comparisons for verification, where possible, data will also be provided to the measurement campaigns with the 22IEM01 TOCK project. In summary, this project will continue the successful fundamental research of 17FUN07 CC4C and 20FUN01 TSCAC on optical clocks and provide high accuracy ion-based optical clocks as future SI standards.

To develop improved methods for trapping and cooling large ensembles of ions, for use in advanced ion-based optical clocks.

So far, ion traps for optical clocks have been optimised for the confinement of single ions. Ion traps that confine single ions and enable highest accuracy were developed in much earlier projects, e.g. EMRP 15SIB03 OC18, and further advanced within EMPIR 18SIB05 ROCIT and 17FUN07 CC4C. Within the 20FUN01 TSCAC project, ancillary ions, co-trapped with the ion species that provides the reference transition, have been investigated. Thereby, composite systems with superior performance have previously been achieved and have created the basis to further increase the number of trapped ions and, in turn, the clock performance. This project will go beyond the current state of the art and demonstrate new methodologies for trapping and cooling large ensembles of ions. As part of this, (i) ion traps with ultra-low heating rates, (ii) the use of superconducting materials at cryogenic temperatures for shielding of electromagnetic fields, (iii) the confinement of ions in engineered static electric and optical fields will be ground breaking for trapping. Further to this, the use of narrow atomic transitions for fast motional ground-state cooling and minimum temperature rise of the ion

crystal during state detection will provide this project with the prerequisite to improve frequency stability and accuracy.

To increase the frequency stability of ion-based optical clocks by a minimum of factor of 2 by simultaneously interrogating 4 or more ions.

The most advanced ion-based optical clocks are currently limited in frequency stability by the quantum nature of their single reference ion. Therefore, this project will advance performance by at least a factor of two by enabling ion-based optical clock operation with four or more ions. This requires an assessment of all technical noise sources so that the maximum number of quantum absorbers can be used. Further advancement in this project, is expected from the use of quantum control techniques, entanglement and spin squeezing, to increase ion-based optical clock performance.

To develop multi-ion based optical clocks with uncertainties below 10^{-18} and to verify their performance via interspecies clock comparisons.

While single ion clocks have now demonstrated uncertainties below 10^{-18} , this project will show that the same accuracy or even superior accuracy can be obtained when using larger numbers of reference ions. Such an assessment of frequency shifts will provide detailed determinations of shifts from external electric and magnetic fields including thermal radiation, collisions between the trapped ions and background gas molecules that are expected to differ from the realisations with single ions. To verify the evaluations, this project will demonstrate their performance via interspecies clock comparisons. In this way, potential unconsidered frequency shifts will become directly detectable.

To develop improved and reliable techniques for optical clocks, using novel reference transitions of HCl and ^{229}Th nucleus, in the VUV and XUV ranges.

As a complementary approach to the use of larger ensembles of ions to reduce the statistical uncertainty, this project will also investigate reference transitions at higher frequencies in the thorium (^{229}Th) nucleus and in HCl. For both systems (i.e. ^{229}Th and HCl), pioneering work was pursued in 17FUN07 CC4C and 20FUN01 TSCAC. In addition to the benefits for frequency stability, the transitions in both systems are also expected to show minimal sensitivity to external perturbation thus permitting higher accuracy.

Outcomes and impact

The impact of this project, in terms of the development and deployment of highly accurate ion-based optical clocks will be predominantly on (i) European metrological capabilities, (ii) the scientific community and (iii) the long-term development of metrological capabilities at the frontiers of measurement science, which will support a future redefinition of the SI unit second. Longer-term economic impact from knowledge transfer to industry is also foreseeable.

Outcomes for industrial and other user communities

Optical clocks are attracting much interest in different sectors, such as space, aerospace, telecommunications and energy networks because of their superior performance compared with established microwave clocks. Key subsystems of optical clocks (e.g. laser systems, reference resonators, frequency combs, ion traps and optical traps) are also already commercially available from several vendors. The first demonstrators of future commercial clocks, for applications beyond fundamental research, have been developed directly by involving industry within a variety of other projects supported by quantum technology initiatives. Sub-components of these first demonstrators of future commercial clocks could be extended to other applications such as precision spectroscopy and quantum information processing.

Several project participants in this project have strong links with European and national programmes that aim to develop optical clocks for applications beyond fundamental research e.g. the German Opticlock project, the Austrian AQUclock project and the Horizon Europe AQURA project. Therefore, this project will help to strengthen and widen the relationships between NMIs, academic institutes and industry through knowledge exchange and cooperation. For example, in this project an industry prototype of an optical clock will be used in comparisons with other high-performance ion-based clocks. Following the comparison, the company will be informed about the observed performance and can then use this information to further advance their prototype clock. To facilitate the use of multiple ions in more compact optical clock setups, the consortium intends to invite an external collaborator to apply the methodologies developed in the project to the case of compact ion-based clocks. This will also ease the future industrial uptake and pave the way towards industrial optical clocks

using multiple reference ions. Moreover, industrial development of optical and electronic systems for high accuracy optical clocks will be supported by the participating NMIs via guidance on target specifications for novel applications and support in the characterisation of commercial prototypes. The project will also identify and involve industrial stakeholders in project workshops and lectures and engage them via social media channels.

Outcomes for the metrology and scientific communities

This project will improve the level of uncertainty realisable with optical atomic clocks by enabling the use of multiple ions, advanced interrogation techniques and transitions at higher frequencies in novel reference systems. This will provide input to the selection of suitable reference systems for a future redefinition of the SI second, an essential contribution to fundamental metrology and to the long-term development of the SI system of units.

This project will also foster new interdisciplinary links, and lead to an exchange of technology and knowledge between high-precision optical frequency metrology, nuclear physics and fundamental physical research. High precision traceable measurements of atomic parameters will additionally contribute to an improved understanding of the structure of atoms, molecules and nuclei.

The data obtained in this project's comparison of high-performance clocks will provide stringent tests of fundamental physical principles (e.g. Einstein's equivalence principle, special and general relativity). The project's results should also benefit searches for so-called new physics effects including potential variations of fundamental constants and the understanding of the composition and interaction of dark matter.

Further to this the project will disseminate its outcome to the metrology and scientific communities via project workshops, lectures, conferences, publications and a summer school for young researchers.

Outcomes for relevant standards

This project will develop and strengthen the high-level metrological infrastructure in the measurement of time and frequency, and in the longer term it will improve the capabilities in time scale generation and time dissemination. Thus, the main impact in standardisation will be through the BIPM's Consultative Committee for Time and Frequency (CCTF) and its working groups; the Frequency Standards Working Group (WGFS) and the Working Group on Primary and Secondary Frequency Standards (WGSPSFS). The consortium is well represented on these committees, where information on the project progress and outputs will be disseminated through presentations and reports. In particular, the project's results of clock comparisons are expected to impact the list of recommended frequency values maintained by CCTF's working groups.

Reports on the project outputs will also be presented to other working groups of the CCTF, such as the Working Group on Strategic Planning (WGSP), which is responsible for updating as necessary the international roadmap towards a future redefinition of the SI second. Further to this, the project will provide input to the EURAMET Technical Committee on Time and Frequency (TC-TF), which is responsible for the cooperative structure of time and frequency metrology laboratories in Europe. In addition, the results will be reported to the European Metrology Network for Quantum Technologies (EMN-Q), in particular to information on quantum clocks and atomic sensors, and feedback will be collected.

Longer-term economic, social and environmental impacts

The longer-term impact of this project will result from the pivotal role of atomic clocks in future revisions of SI units and in growing technology sectors. Improved techniques to compare atomic clocks and the development of trapping and cooling techniques are relevant for technological applications, in sectors such as navigation, space, aerospace, telecommunications, energy networks and the field of quantum simulation and quantum information processing. Further to this, trapped ion optical frequency standards combine excellent accuracy with the potential for miniaturisation of both the "physics package" (i.e., ion trap, vacuum systems, and optical setup for cooling and detection) and the cooling lasers, which is of major importance in their development as payloads on board satellites and aerospace vehicles. Therefore, in the longer-term ion-based optical clocks with improved frequency stability will support geodesy measurements with cm-level precision and applications in geodynamic and climate research.

Project start date and duration:		1 st May 2024 (36 months)
Coordinator: Nils Huntemann, PTB Tel: +49 531 592 4430 E-mail: nils.huntemann@ptb.de Project website address: https://www.ptb.de/epm2023/HIOC		
Internal Beneficiaries: 1. PTB, Germany 2. BEV-PTP, Austria 3. CMI, Czechia 4. INRIM, Italy 5. VTT, Finland	External Beneficiaries: 6. ISI, Czechia 7. LUH, Germany 8. MPG, Germany 9. TU WIEN, Austria	Unfunded Beneficiaries:

Publishable Summary for 23FUN04 COMOMET

Fundamental physical metrology with cold molecules

Overview

Recently, academic research laboratories have developed advanced instrumentation to cool, manipulate and investigate molecules with extremely high precision, reaching frequency measurements with 13 digits of accuracy, in some cases. This project aims to unlock the potentials of applying cold molecules in metrology, including the need for establishing frequency standards in the infrared (IR) spectrum, testing the fundamental laws of physics that underpin basic metrological principles, such as fundamental symmetries and variation of fundamental constants, and improved determination of fundamental constants, like the proton-to-electron and the deuteron-to-electron mass ratios, the Rydberg constant, and the proton and deuteron charge radii. In this project, fibre-optic connections built during previous EURAMET projects (e.g. EMRP JRP SIB02 NEAT-FT and EMPIR JRPs 15SIP04 TIMEFUNC, 17IND14 WRITE, 15SIB05 OFTEN and 18SIB06 TiFOON) will be used and further extended in terms of number of connections and km. Strong collaboration between NMIs and academic participants will lead to full exploitation of frequency references delivered via such fibre networks for molecular spectroscopy experiments.

Need

Fundamental constants are a cornerstone of metrology. At present, the precision and accuracy of the measurement of fundamental constants are bottlenecks for verifying physical models. These models need verification, especially in connection with the redefinition of standards. The potential for precise measurements of fundamental constants using molecules is now being realised. For example, two independent studies (VU and HHUD) recently improved the accuracy of the proton-to-electron mass ratio (β) to 21 parts per trillion through measurements with hydrogen molecular ions.

In addition to measuring constants, verifying their temporal stability is equally important. Many theories of new physics that aim to explain the nature of dark energy or unify gravity with other forces, predict that the fundamental constants change either in time, in space, or with the local mass density. These predictions can be tested by comparing atomic and molecular clocks of different types which is now possible due to dedicated optical fibre networks linking European NMIs and several other institutions. Molecular clocks are especially sensitive to variations of β . To be relevant, these clocks must reach an accuracy of 10^{-17} or better, which requires extremely stable lasers and ultracold molecules: The rovibrational transitions of simple molecules are typically in the mid-infrared (mid-IR), where there is an urgent need for improved frequency standards. Laser technology is poor in this part of the spectrum, requiring substantial development beyond the current state of the art.

At present, know-how on cold molecules lies mainly in research laboratories outside the NMIs. Therefore, collaboration with several leading non-NMI laboratories is needed at this stage. To ensure the techniques and results of cold molecule research become useful for metrology, state-of-the-art methods developed in academic research groups need to be advanced from the perspective of NMIs, including the services they provide for end-users, such as new frequency standards in the IR.

Objectives

The overall aim of this project is to develop cold and ultracold molecules, and ultra-stable lasers into useful tools for defining new frequency standards, measuring fundamental constants, and verifying their stability.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP

EURAMET

Issued: June 2024

The specific project objectives are:

1. To improve the determination of fundamental constants, such as the proton-to-electron and the deuteron-to-electron mass ratios, the Rydberg constant, and the proton and deuteron charge radii, by performing high resolution spectroscopy on simple, calculable molecular species, either ions, neutrals, or Rydberg molecules.
2. To develop mid-infrared (mid-IR) frequency standards based on ultracold molecules, aiming for a linewidth below 10 Hz, a stability of 2×10^{-15} at 1 s, and the potential to measure the stability of the electron-to-proton mass ratio to a fractional precision better than 10^{-17} per year.
3. To develop metrology-grade, highly stable, SI-traceable and widely tuneable laser sources in new and extended regions of the mid-infrared (mid-IR) and THz. The stability should be 10^{-15} or better. Tunability should be tens of GHz, corresponding to the typical spectral window of distributed-feedback mid-infrared quantum cascade lasers.
4. To develop ultra-high-resolution spectrometers from the microwave to the UV spectral window, with fractional accuracies ranging from 10^{-12} to 10^{-15} in the mid-infrared and 10^{-10} to 10^{-12} for THz/Far-IR. These will be based on the SI-traceable ultra-stable sources developed in objective 3 and on efficient and continuous sources of buffer gas-cooled molecules, in particular metal hydrides, metal halogens, and complex molecules.
5. To facilitate the technology transfer by the European research community working on infrastructures and methods by creating a coordinated and optimised strategy for the long-term development of a framework allowing simultaneous, and potentially synchronised, SI-traceable frequency measurements on different molecular systems, at different locations in Europe.

Progress beyond the state of the art and results

Objective 1 - Fundamental constants.

Very recently, values of β ($= m_p/m_e$) were reported with 0.02 ppb precision from molecular-hydrogen-ion spectroscopy. The main limitations stem from the ~ 0.01 ppb precision of theoretical predictions and on the uncertainty of local atomic clocks. Transitions in molecular hydrogen, ions and neutral, depend on several other constants besides β - the deuteron-electron mass ratio (m_d/m_e), Rydberg constant (R_∞), proton and deuteron charge radii (r_p , r_d), and the fine-structure constant (α). This requires measurements of several transitions in different calculable molecular systems.

This project aims to improve the precision of m_p/m_e and m_d/m_e by a factor 2-3, and determine other constants, through measurements of rovibrational energies, dissociation energies and ionisation energies of neutral and ionic molecular hydrogen. The consortium aims to improve the accuracy of *ab initio* theory, of experiment, and of frequency references. The project participants also aim to reduce the experimental uncertainty to 4 % of the proton finite size contribution, sufficient to resolve the Proton Radius Puzzle without input from muonic hydrogen spectroscopy. Fibre-optic links to NMIs will ensure traceability of fundamental constants to the SI second.

Objective 2 - Mid-IR frequency standards and the stability of $\beta = m_p/m_e$.

There are currently only three secondary frequency standards in the IR recognised by BIPM, which are 3-6 orders of magnitude less precise than frequency standards in the microwave or optical domains. The best limits on the stability of β come from measurements with atomic clocks. While optical atomic clocks are insensitive to β , microwave clocks depend on β because the hyperfine frequency depends on the nuclear magnetic moment. Comparisons of optical and microwave clocks constrain the drift rate below 4×10^{-17} per year. This is a model-dependent result, often considered to be indirect. Direct model-independent measurements have been made using SF₆ molecules by some of us and, more recently, ultracold KRb molecules. These measurements determine a drift rate below 10^{-14} per year.

This project aims to develop new standards based on vibrational transitions in trapped molecules. The project participants choose systems with narrow linewidths that have little sensitivity to environmental perturbations. These frequency standards will also be sensitive probes of the stability of β . The molecular ion program will focus on meeting the stability and reproducibility requirements of an NMI environment, including the optimisation of molecular ion production, internal state preparation, sympathetic cooling, and new protocols for

quantum logic spectroscopy. The neutral molecule program will develop optical traps for ultracold molecules and study systematic shifts of their vibrational transitions.

Objective 3 - Mid-IR laser sources.

Coherent sources for precision spectroscopy require high intensity, narrow linewidth, high frequency stability, and traceability against the primary frequency standard. Room-temperature quantum cascade lasers (QCLs) can emit in the 4–17 μm range with mW-to-W powers, while cryogenic QCLs reach beyond 80 μm with linewidths in the sub-Hz to kHz range. Mid-IR radiation can also be generated by difference frequency generation (DFG) of powerful CW lasers. Methods have been developed to lock mid-IR radiation to near-IR ultra-stable references located in NMIs and ultimately referenced to the SI standard. This is achieved using an optical fibre link that disseminates an ultra-stable reference, and a frequency comb and non-linear optics to bridge the gap to the mid-IR. This provides frequency stabilities below 10^{-15} from 0.1 to 10 s and uncertainties in the 10^{-14} range or better. It also paves the way for new measurements on molecules, but it has only been demonstrated at $\sim 6 \mu\text{m}$ and $\sim 10 \mu\text{m}$. So far, only a few rovibrational frequencies (of CO, OsO₄, CH₃OH, HCOOH) have been measured with uncertainties in the 10^{-11} and 10^{-12} range. Current limitations come from the lack of commercial QCLs and of efficient nonlinear crystals for frequency conversion above the $\sim 10 \mu\text{m}$ range.

The project participants aim to extend SI-traceability and ultra-high stability to laser sources between 3 and 20 μm . The project participants seek to reduce the linewidths of mid-IR lasers to the Hz-level and tie them reliably to the SI-second. The project participants aim to develop a high-power (2 W) SI-traceable laser source covering the fundamental vibration in neutral molecular hydrogen and its isotopologues (2 – 3 μm) reaching 10^{-14} accuracy, to be used for metrology of the highest precision in calculable molecular systems. The project participants also aim to solve technical issues which impair the performance of mid-IR lasers, including control of the laser beam spatial profile, and new materials for polarisation control and optical fibres. Moreover the project aims to improve the performance of THz sources, especially THz quantum cascade laser frequency combs. Therefore the SI-traceability will be extended and the stabilization of these devices will be employed in high precision spectroscopy. The project participants will explore the upconversion of THz combs into a telecom carrier for signal distribution.

Objective 4 - Ultra-high-resolution molecular spectrometers

Cryogenic buffer gas cooling is a versatile technique for cooling molecules to a few kelvin, and producing intense, slow-moving molecular beams. The technique is the starting point for laser cooling and magneto-optical trapping of molecules. Early work focussed on small diatomic molecules, but the method is now being extended to more complex species. IC with CNRS have demonstrated buffer gas cooling of methyltrioxorhenium, a low volatility species of interest for testing the parity symmetry and demonstrated the first precision spectroscopic measurements of buffer-gas cooled molecules in the mid-IR.

The project participants will extend the cryogenic buffer gas method aiming at new species such as metal halogens, and complex, heavy and low-volatility polyatomic molecules. The project's long-term aim is to reach the same degree of cooling and quantum control now available for diatomic molecules. The slow-moving beams will yield longer interrogation times, resulting in increased resolution. The project participants will couple these buffer-gas sources to sub-Doppler spectrometers and Ramsey interferometers.

Objective 5 - Simultaneous, synchronised, SI-traceable frequency measurements on molecular systems across Europe.

At present, most universities and research organisations (ROs) use their own frequency standards as a reference for molecular spectroscopy. Very few ROs have continuous traceability to an NMI via optical fibre. However, technology for optical fibre time and frequency transfer and stabilised laser wavelengths exists and has been demonstrated in previous EMRP and EMPIR projects such as EMRP JRP SIB02 NEAT-FT, EMPIR JRP 15SIP04 TIMEFUNC, EMPIR JRP 17IND14 WRITE, EMPIR JRP 15SIB05 OFTEN and EMPIR JRP 18SIB06 TiFOON. That technology is now ready for deployment to universities and ROs in need of SI-traceable signals to support measurements on cold molecular systems. In cases where optical fibre links are not yet in place, the research organisation can be linked to an NMI via GNSS time and frequency transfer. By means of GNSS common view or GNSS PPP links, the difference between a local reference clock at the research organisation and the UTC realisation of an NMI or DI can be continuously monitored, and results corrected for deviations.

The project participants will provide frequency references to more laboratories by connecting them to NMIs via fibre links where possible, or by satellite. This will result in a European network of laboratories that can make frequency measurements at the ultimate accuracy. This new network of connections will link laboratories with one another, enabling experiments distributed over the whole continent. Finally, the network will provide the basis for synchronous experiments at different locations. This is important for clock comparisons, and in searches for new physics.

Outcomes and impact

Outcomes for industrial and other user communities

Advances in basic sciences often lead to the creation of new measuring devices and to new areas of technological possibility, with all the economic and societal benefits this brings. Ultracold atoms are a good example. For many years they were an exotic curiosity confined to research laboratories, but they are now at the heart of several commercial devices including magnetometers, accelerometers, gyroscopes, gravimeters, and inertial navigation systems. They have also led to quantum memories, quantum communications and quantum information processing. Molecules have many degrees of freedom absent in atoms which offer rich possibilities for new technology and innovative measuring devices. The control of all degrees of freedom, and of molecular interactions, are the keys for controlling chemical reactions with implications ranging from the production of new materials to new ways of energy generation and storing, from biological to pharmacological molecules. Finally, due to their strong, long-range dipole-dipole interactions, ultracold molecules make an ideal platform for quantum simulation and information processing. All these applications are actively being pursued.

The project will develop a new class of metrology-grade, highly-stable, narrow-linewidth and widely-tunable IR coherent sources in the range between 6 and 20 microns. These can be used for molecular sensing and trace gas detection in the “fingerprint region”, where molecules exhibit their characteristic vibrational spectrum. The developed methods will enable the detection and quantitative analysis of trace quantities of weakly -interacting molecules and rare isotopes. One example is the detection of “difficult-to-measure radioisotopes” such as ^{14}C , ^{36}Cl , ^{90}Sr , and ^{107}Pd , which could be monitored in real time in nuclear power plants or during their decommissioning, to safeguard workers and the environment. In medicine, improved molecular tracing can be used to develop new breath analysis tests to better understand diseases and predict, prevent, diagnose and treat them. This opens the door to personalised therapeutic strategies, to determine predisposition to disease and to deliver timely and targeted prevention. Trace gas detection in the 3–5- μm and 8–13- μm windows, where the Earth’s atmosphere is relatively transparent, is important for environmental monitoring and atmospheric studies, particularly regarding global warming. Secure optical communication may also benefit from the improved photonics devices developed in this region. The development of mid-IR optical isolators, beam-profile shapers, and optical fibre may be important for the photonics and telecommunications industries as well since visible and near-IR miniaturized optical systems can be found in everyday use devices.

Outcomes for the metrology and scientific communities

The development of extremely stable and traceable lasers together with colder and denser molecular samples and techniques for trapping them, will allow for molecular spectroscopic measurements of unprecedented frequency resolution and precision. Frequency measurements at the 10^{-15} level of precision or better will be achievable. The improved knowledge of fundamental constants and their stability will be of primary importance for metrology. There are currently only three secondary frequency standards in the IR recognised by BIPM, and they are 3-6 orders of magnitude less precise than frequency standards in the microwave or optical domains. This work will result in new IR frequency standards of higher precision.

Theories of physics beyond the Standard Model which seek to explain dark energy, dark matter, and the imbalance between matter and antimatter, amongst other things, can be tested using precise measurements with molecules. The methods developed in this project will enable tabletop tests of fundamental physics which are complementary to experiments at high energies facilities. Examples which test new theories include molecular measurements of the electron’s electric dipole moment, measurements of time-varying fundamental constants, and molecule-based measurements of nuclear parity violation. In addition, accurate knowledge of the frequency, line shapes, and intensities of molecular transitions will benchmark atmospheric physics measurements and astrophysical observations, and will be used to validate quantum chemistry calculations.

The infrastructure for fibre-optic frequency transfer developed in recent years is a unique facility which is ideal for performing the metrological activities of this project, both inside and outside NMIs and DIs. The project will

ensure a coordinated and optimised strategy for the long-term development of a European fibre network infrastructure, through a collaborative European approach.

Outcomes for relevant standards

In metrology it is assumed that fundamental constants are stable in time and space, based on accurate measurements of their values. The project participants aim to reduce the uncertainty on the value of m_e/m_p by a factor 2-3 and prepare the tools needed for even more precise measurements, i.e. better lasers and colder molecular samples. Any updated values of constants measured will immediately be provided to CODATA. The project will develop improved frequency references in the mid-IR for recommended wavelengths. The participants will communicate the project results to BIPM Consultative Committee for Time and Frequency (CCTF), EURAMET Technical Committee on Time and Frequency (EURAMET TC-TF) and CCL-CCTF Frequency Standards Working Group (WGFS).

Longer-term economic, social and environmental impacts

The new European growth strategy, based on the European Green Deal, aims at reaching climate neutrality before 2050. Molecular spectroscopy is an excellent tool for monitoring the composition of Earth's atmosphere. A critical requirement for the instruments aimed at monitoring the global warming effect and climate change is reaching at least 0.1 % accuracy in determination of the abundance of the relevant molecules in the atmosphere. This can be achieved only if the positions, intensities, and shapes of molecular absorptions are known with corresponding accuracy.

Industries will benefit from the project results, which will strengthen the European industrial infrastructure for the development of new services and products that rely on optics and photonics. As a wider impact, Europe's innovative capacity should be increased, leading to higher employment and wealth for society. The project will improve collaboration between NMIs and, more importantly, between NMIs and other research institutions. Finally, this project contributes to a better understanding of Nature. Satisfying human curiosity is perhaps the most important contribution hoped for.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2024, 36 months
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRIM, Italy	5. AU, Denmark	-
2. GUM, Poland	6. CNR, Italy	
3. OBSPARIS, France	7. CNRS, France	
4. VSL, Netherlands	8. HHUD, Germany	
	9. UMK, Poland	
	10. VU, Netherlands	
Associated Partners:		
11. ETHZ, Switzerland		
12. IC, United Kingdom		
13. METAS, Switzerland		
14. UNIBAS, Switzerland		
Affiliated Entities: 15. UEVE, France (Affiliated to CNRS)		

Publishable Summary for 23FUN05 AQuanTEC

Advanced quantum technology for metrology of electrical currents

Overview

Advances in high fidelity control of electrons provide a fundamental resource for a vast number of facets in quantum technologies and could enable most demanding applications in electrical current metrology. Single-electron pumping, supplemented by combining Josephson and quantum Hall effect, provides a wide range direct link to the SI. To fully unleash the potential of single charge control for quantum metrology and technology, this project will investigate advanced methods to close the impending nA-gap in direct quantum current generation, examine the fundamental uncertainties of single-electron pumps, and explore novel device concepts exploiting technological advances driven by solid state quantum technology research.

Need

Quantum is the next frontier in physics that technologies across the board are conquering. Major efforts are in progress to meet the challenges of digital transformation. Quantum is also a cornerstone for metrology, and the technological challenge is to connect to quantum definitions at the best possible accuracy and accessibility. In electrical quantum metrology, the prime examples of robust primary quantum standards are the Josephson voltage standard and the quantum Hall resistance standards, which directly exploit the definition of the SI by fundamental constants. In contrast, a complementary direct, wide range, gapless, and robust primary quantum standard for electrical currents is still elusive for the wide range of small current levels. This gap needs to be closed, exploiting the directly controlled transfer of elementary charges, complemented by direct combination of Josephson and quantum Hall effect, to realise a consistent and robust future-proof electrical quantum metrology system.

The accurate measurement of small electrical currents has many key application areas such as environmental monitoring, energy efficiency, climate research, nuclear safety, medical applications and digital transformation. The long-term progress in these areas and increasingly demanding European goals and regulations need to be backed by a capable metrology of electrical currents. Ensuring the highest possible accuracy and stability level requires the provision of primary quantum standards of the electrical current.

The resulting technical needs can be divided into four categories: (i) To realise a continuous range of quantised current sources, quantised single-electron pumping and sources directly combining Josephson and quantum Hall effect need to be scaled into the uncharted current range from 0.1 nA to 1000 nA (objective 1). (ii) Improving uncertainties of quantised single-electron sources and providing trust requires new approaches to uncertainty evaluation and the identification of ultimate accuracy limits of these quantum devices (objective 2). (iii) To further advance quantum electrical metrology and to provide new opportunities for quantum technologies, it is essential to explore advanced semiconductor and superconductor quantum technologies for novel current device concepts, utilising qubit technologies and charge-phase duality in the Josephson effect for quantised charge pumping with great potential for upscaling of the current level (objective 3). (iv) The implementation of wide-range quantised current sources requires developing and implementing new quantum technologies for device scaling and validation (objective 4).

Objectives

The overall objective of this project is to achieve a **primary quantum standard of the electrical current** that, based on novel quantum technologies, is direct, wide range, gapless, and robust. In specific, the project will develop scaling of quantum current sources and assess their uncertainty limits; it will explore novel device concepts and implement advanced quantum technologies.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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EURAMET

Issued: May 2024

The specific objectives of the project are:

1. **To realise a continuous wide range of primary quantum current sources** for electrical currents from 1 fA to 1 mA by investigating and evaluating the scaling of quantised currents into the nA range (i) via upscaling semiconductor single-electron pumps to quantised currents > 1 nA by parallelisation and (ii) via downscaling the quantised currents generated by a direct combination of Josephson voltage sources and advanced quantum Hall resistance standards to currents < 10 nA.
2. **To evaluate the uncertainties of semiconductor single-electron pumps** and provide traceable measurements of the quantised current, with a target uncertainty below 1 part in 10^7 . To perform single-electron detection of individual rare error events inside and outside the quantised current regime. To develop and experimentally evaluate advanced models of single-electron capture and emission.
3. **To explore the metrological potential of novel device concepts for direct quantised current generation**, such as semiconductor qubit devices and dual Shapiro step based superconducting current sources. To experimentally realise quantised currents using these devices. To evaluate the intrinsic sources of systematic uncertainties (e.g., gate leakage, temperature dependence, etc.). To characterise their output currents using traceable current measurements, with target uncertainty less than 1 part in 10^6 .
4. **To develop advanced technologies for devices, cryogenic device control, and ultra-sensitive measurements** required for the implementation and scaling of quantum electrical current standards over the relevant range of current. This will include single-electron pump and quantum Hall standard arrays, multiplexers, cryogenic control modules and scalable integration schemes.
5. **To facilitate the take up of the technology and measurement infrastructure** developed in the project by the measurement supply chain, research organisations (academia, research institutes), standards developing organisations (CEN-CENELEC, CCEM), and end users (fundamental metrology, solid-state quantum technologies).

Progress beyond the state of the art and results

To realise a continuous wide-range of primary quantum current sources (Objective 1):

The state of the art of primary quantum current realisations allows the generation of up to 100 pA by single-electron pumps (SEPs) and currents above 1 μ A by direct combination of a Josephson voltage standard (JVS) and a quantum Hall resistor (QHR). This was a result of the previous EMPIR project JRP 15SIB08 "e-SI-Amp - Quantum realisation of the SI ampere". This project will now implement upscaling of quantised single-electron currents by parallelisation of SEPs, extending the upper current limit from the present 100 pA to the nanoampere range with 1 part in 10^7 target uncertainty. Parallelisation will be realised with advanced on-chip multiplexing schemes for simultaneous optimal device control of many SEPs. Furthermore, this project will perform a downscaling of quantised currents generated by direct combination of JVS and a QHR to currents < 10 nA using large-value QHR arrays for signal scaling and noise mitigation with target uncertainties of 1 part in 10^8 and 10^6 for current values of 1 μ A and 10 nA, respectively. Combined, this will close the current 0.1 – 1000 nA gap of primary quantised current generation.

To evaluate the uncertainty limits of single-electron pumps (Objective 2):

The quantisation accuracy of SEP currents has been probed by precision measurements of the direct pumped current with state-of-the-art measurement uncertainties of a few parts in 10^7 and is limited by the traceability of current measurements at a current level of typically 100 pA. The project will combine novel theoretical approaches, precision measurements, and single-electron counting for a first-principles prediction of accuracy limits for primary quantised SEP current sources in metrologically relevant operation regimes with an expected uncertainty below 1 part in 10^7 . The novel physical modelling of electrons in the shallow cubic-parabolic confinement regime of the quantum dot (QD) used for SEP realisation will be implemented, validated with high accuracy data, the physical parameters determined experimentally for different technologies, and the accuracy limits explored, feeding into the development of quantum metrology.

To explore the metrological potential of novel devices concepts for direct quantised current generation (objective 3):

Large efforts have recently been invested to progress semiconductor and superconductor quantum technologies towards the realisation of quantum IT and sensing. For semiconductor spin qubits, realised using quantum dots, single electron control has been improved. Advances in superconducting Josephson junction

technologies recently allowed the demonstration of Shapiro steps in their current characteristics. The project will utilise the recent advances in semiconductor and superconductor quantum technologies to realise novel quantised current sources: (i) The consortium will evaluate the accuracy of single-electron sources based on silicon qubit device platforms. Starting from spin qubit device layouts and technologies, different single-electron transfer schemes will be realised and tested, and quantum device optimisations implemented. (ii) The project will explore quantised current generation by dual Shapiro step -based devices, manifesting the phase-charge duality in Josephson junctions. System and device optimisations will be used to optimise robustness and accuracy. The accuracy will be assessed for both novel technologies with an uncertainty better than 1 part in 10^6 .

To develop advanced technologies for devices, cryogenic devices control, and ultra-sensitive measurements required for the implementation and scaling of quantum electrical current standards (objective 4):

This project will develop advanced technologies needed for upscaling SEP currents and for downscaling quantised currents generated by combining a JVS and QHR. To date, parallelisation of SEPs was realised only with 2-3 devices and without achieving sub-ppm accuracy; only prototypes of high-value QHRs have been realised and require sub-Kelvin temperatures; multiplexing of quantum dots has only been demonstrated for static conditions. This project will provide: (i) circuits of parallelised SEPs achieving at least a tenfold increase of current without deterioration of accuracy, (ii) high-resistance quantum Hall resistor arrays with up to 100 multi-connected graphene Hall bar elements for quantised resistance values of up to 1.29 M Ω operated above 2 K, (iii) cryogenic multiplexer circuits for simultaneous optimised control of many SEPs, (iv) cryogenic setups integrating multiple quantum standards.

Outcomes and impact

Outcomes for industrial and other user communities

The project will provide primary quantum current sources for electrical currents with a combined wide continuous range from 1 fA to 1 mA. In the current range from 1 fA to 1 nA, this project will use the developed single-electron pumps as a noiseless source of current to test linearity and stability of commercial ammeters. Due to the superior linearity and stability of single-electron sources, the consortium expects to characterise these properties in a range spanning six orders of magnitude, leading to a better understanding of the characteristics of these instruments. Correspondingly, the developed next-generation PQCG will be used in the range 1 μ A down to 10 nA. The project participants will communicate the test results to the instrument manufacturers, as well as to the wider user community. The results will also be used to establish new calibration capabilities. The project participants will consider the revision of their calibration and measurement capabilities (CMCs) in this range of DC current. Industry and others in need of small-current metrology will benefit from the expanded availability of calibration service with improved CMCs, as well as through NMIs' activities through collaborative R&D projects and industry engagement.

Another area that benefits from this project is the quantum industry (and scientific communities in quantum technologies). The outputs from these activities in testing semiconductor qubit-based devices (fabricated in state-of-the-art silicon technology) and superconducting devices with metrological tools will be disseminated to quantum technology communities through publications, conference presentations, and project workshop. Manufacturers of semiconductor spin qubits will benefit from the systematic evaluation of the transfer errors in their devices. Accurate and noiseless on-chip current sources compatible with quantum sensing or IT technologies will become available. This project will create opportunities for networking between the quantum metrology and quantum industry communities. The work on standardisation documents with delegates from academia and the quantum industry in the newly established CEN-CENELEC JTC22 will promote and further develop this technology, especially for upcoming new applications.

Outcomes for the metrology and scientific communities

The project will underpin world-leading European quantum current metrology over a wide current range from 1 fA to 1 mA. The resulting improved accuracy status of current traceability to the SI from quantum technologies (single-electron pumps, PQCG, dual-Josephson based standards) will be compiled and disseminated to various European and international metrology committees to foster the uptake of the project results in electrical current metrology.

The exploitation activities mentioned in the previous section, the linearity and stability test of commercial ammeters using the expected results of single-electron pumps and PQCG, will also have outcomes for the metrological community. These results will be communicated to the metrological community via presentations at technical committee meetings and conferences. In addition, the technological developments and

characterisations of these sources will be published in peer-reviewed journals and presented at conferences. The availability of quantum current standards in the range 100 pA to 1 μ A will very likely result in the development of better secondary standards in this current range.

This project will also have an outcome on the primary resistance metrology. The expected result of graphene quantum Hall arrays with high-value resistance of up to 1 M Ω (and those at intermediate values down to 12.9 k Ω) will create benefits on the high-value resistance calibration by removing the limitation of resistance in the existing methods using the cryogenic current comparator. The range will be expanded significantly. In addition, the design of the quantum Hall resistance amplifiers developed in this project will be made available with an open licence. This will allow the uptake and implementation of the technology by stakeholders in the metrological and scientific communities.

Outcomes for relevant standards

Several committees are handling different aspects of developing quantum metrology and traceable measurement technology. Several members of the consortium, especially the NMIs, are already taking an active and leading role in these committees by providing the chair or convenor, e.g., the chair (INRIM) and vice-chair (PTB) of the European Metrology Network for Quantum Technologies (EMN-Q), which provides active coordination of European measurement science research to maintain competitiveness in the field of quantum technologies. The Technical Committee for Electricity and Magnetism and the Subcommittee DC and Quantum Metrology of EURAMET already have a strong interaction with the consortium, being long-time members and convenors (PTB) in these committees. The Joint CCEM-CCRI Task Group on Low Current Measurement (convenor NPL) and CCU Focus Group on counting and number quantities of the BIPM are also highly relevant committees. All significant project progress and results will be brought to the above-mentioned committees' attention.

To promote the technological uptake of the results of this project and the accumulated expertise from the consortium on single-electron sources, a new work item to write a CEN-CENELEC technical report (TR) will be established with other partners in academia and industry. The leading role of the Joint Technical Committee on Quantum Technologies (JTC 22) will help Europe to have a strong, unified voice in the upcoming international standardisation of QT at ISO/IEC. IEC SEG 14 recently recommended IEC SMB to establish a ISO/IEC JTC-Q in a timely manner (voting at NSBs already closed, JTC-3 starts presumably May 2024). Consortium members will participate in these activities and will ensure a strong, consensus European voice, regarding all topics related to single-electron sources.

Longer-term economic, social, and environmental impacts

Electricity is ubiquitous in the society. Improved metrology leads to the creation of new and improved products and services, enhancing economic activities and improving the quality of life. Electrical metrology has a significant weight in this considering the vast number of electronic devices used in the modern society. Providing building blocks for a primary quantum realisation of the ampere and enhancing the NMI's capabilities in high-precision measurements, the results of this project will finally lead to improved industrial small current measurement capabilities with reduced uncertainty, fostering the development of and enabling future products and services. Economic impacts from specific project results are expected for the semiconductor industry in their effort for ultimate device scaling (results on quantum effects and error mechanism in single-electron nanoscale CMOS devices) and for the quantum industries (single-electron transfer, novel quantum devices for future applications).

The improved metrology of small electrical currents will lead to improved measurements in many other metrology areas, where sensing signals are converted into a small electrical current. Examples are ionising radiation intensity, impacting nuclear safety and medical applications; light intensity with impacts on energy efficiency and climate monitoring; aerosol concentration measured in air pollution monitoring. Such improvements will support the long-term progress in related application areas and will underpin the monitoring of increasingly demanding European goals and regulations with many positive effects for health and for the protection of the environment.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 May 2024, 36 months	
Coordinator: Frank Hohls, PTB		Tel: +495315922530	E-mail: Frank.Hohls@ptb.de
Project website address: https://www.ptb.de/epm2023/aquantec/			
Internal Beneficiaries:		External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany		6. CEA, France	n/a
2. INRIM, Italy		7. CNRS, France	
3. LNE, France		8. FZ-Juelich, Germany	
4. RISE, Sweden		9. LatU, Latvia	
5. VTT, Finland		10. POLITO, Italy	
		11. SemiQon, Finland	
Associated Partners:			
12. AIST, Japan			
13. KRISS, Korea, Republic of			
14. NPL, United Kingdom			

Publishable Summary for 23FUN06 ProMET

Fundamental protein metrology to support the definition of measurands, analytical targets, and their associated measurement uncertainty

Overview

Proteins are dynamic and heterogeneous biomolecules whose accurate quantification is key in sectors such as food, health and biopharma. Unravelling protein structures, their interactions, and the relationship to function are critical for accurate and comparable protein measurements. However, the metrology community has only recently started to address the developments for measurements of the higher-order structures of proteins. In addition to this, the definition of the measurand is complex for heterogeneous molecules such as proteins which are measured by different techniques. This project will investigate overall protein structures and their influence on measurements and protein function. The project will also develop a metrology framework and guidelines to better define the measurands, analytical targets and estimate measurement uncertainty for proteins.

Need

Proteins are complex macromolecules that perform vital biological functions in all living cell processes. Proteins consist of a sequence of building blocks called amino acids. The overall structure can be constituted of a sequence of amino acids (primary level), its folding in alpha helices or beta sheets in space (secondary level), the arrangement of the alpha helices and beta sheets in space (tertiary level) and the aggregation of several sequences (quaternary level). The protein's function is strongly associated with its overall structure and can be affected by structural changes that may result from (i) genetic variations, (ii) alternatively spliced RNA transcripts or (iii) post-translational modifications (PTMs). Thus, any given protein may result (due to structural changes) in a complex mixture of different protein versions named proteoforms.

Protein measurement can be affected by the presence of different proteoforms of the protein and the measurement principles used, which in turn can lead to discrepancies in measurement results. Therefore, reliable and comparable measurements are needed as well as improved confidence in the data for proteins. This information is crucial for life science sectors such as food industry, food safety, health diagnosis, biopharma, and doping control. Given the complexity and heterogeneity of proteins and their structures, one of the main challenges is defining the measurand. This is further complicated by the different techniques used for protein measurement, as these rely on analytical targets that usually differ from the measurand.

The following are needed to address these challenges:

- development of accurate methods for the characterisation of the whole protein structure (primary to quaternary),
- robust evaluation of the impact of protein structure on measurement results,
- improved metrological developments focused on protein primary structure to higher order structure (HOS) (i.e. secondary, tertiary and quaternary structure is often collectively termed as HOS) protein analysis,
- tools to support better definition of the measurand(s) associated to specific proteoform(s).

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: September 2024

Addressing these needs will require a multidisciplinary approach and collaboration between researchers, metrologists, and key stakeholders in the life science sectors in order to improve the accuracy and reliability of protein measurements.

Objectives

The project's overall goal is to develop strategies to better understand the influence of protein structure on protein measurement and function and to establish a metrology framework with a better description of the protein measurand, the analytical targets and their influence on the measurement uncertainty.

The specific objectives are to:

1. To investigate the influence of primary sequence variants and PTMs of proteins, such as glycosylation, phosphorylation, deamidation, oxidation, or glycation on quantitative measurement results. Protein materials of increasing complexity will be characterised by expanding conventional metrological approaches based on mass spectrometry (MS) and nuclear magnetic resonance (NMR).
2. To investigate the influence of the primary sequence and PTMs variants considered in the Objective 1 on the secondary and tertiary structure of the protein and the influence of the presence of different structure variants (from primary to tertiary) on protein-protein interactions. This will be achieved by developing fit-for-purpose strategies using native and structural MS (e.g. ion mobility spectrometry-MS (IM-MS), hydrogen deuterium exchange MS (HDX-MS), chemical cross-linking MS (XL-MS)) combined with other biophysical approaches (e.g. dynamic light scattering (DLS), cryoEM, and NMR) and existing computational techniques to characterise the higher-order structure (HOS) of the proteins to distinguish and quantify different structures and to explore the protein-protein interactions observed in biological systems (e.g. antibody-antigen interactions). Protocols to ensure traceability and estimation of the measurement uncertainties of the results will be developed.
3. To study the impact of structure heterogeneities from objective 1 and 2 on the measurement procedures using either purified peptides, recombinant proteins, extracted proteins or endogenous proteins in simplified buffer or matrix-matched solutions as calibrators. The influence of structure and interactions on isotope dilution-based reference measurement procedures (RMPs), and routine methods using proteomics approaches and immunoassays including sample preparation, calibration and incorporation of isotopically labelled analogues will be investigated.
4. To determine mathematical models based on the results of Objectives 1 to 3 to understand the influence of interferences, protein structure and protein-protein interactions on the different measurement procedures and evaluate their influence on protein function. Approaches to estimate the appropriate measurement uncertainty associated with procedures targeting entities that are not the intended measurand will be developed. Based on the measurement results and the model outcomes, guidelines will be developed for the definition of protein measurands (including appropriate units), of the analytical targets and the estimation of measurement uncertainty for the routine methods and the method developed within the project.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, research laboratories), research organisations (European Metrology Networks (EMNs) on Traceability in Laboratory Medicine and Safe and Sustainable Food), standards developing organisations (International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), ISO and Codex Alimentarius.) and end users (biopharma, biomedicine, food producers, academic laboratories and clinical diagnostic laboratories).

Progress beyond the state of the art and results

A proven way towards reliable and comparable results is to establish the results' metrological traceability to the international system of units (SI). The metrology community is currently developing tools, such as RMPs for the purity assessment of peptide and protein materials in order to produce reference materials (RMs). However, to date, most of these RMPs determine the protein content based only on the proteins primary structure and protein modifications are not addressed.

This project will advance the state-of-the-art by:

- developing cutting-edge analytical approaches, mainly using MS, and a new metrological framework for the whole structure characterisation of proteins (i.e. primary, secondary, tertiary and quaternary) in a pure solution material,
- extending the knowledge on the influence of the primary structure and HOS on protein measurements.

Characterisation of the primary structure: sequence variants and PTMs (Objective 1)

Metrological purity assessment has been applied to peptide materials with ≤ 30 amino acids. Quantifying the target peptide is currently well established, however challenges arise in identifying and quantifying impurities. Further to this, the move from peptides assessments to proteins represents additional challenges due to protein size, complexity, and the potential number, size and structure of the impurity present in pure samples.

This project will go beyond the state of the art by developing alternative methods to the widely used but costly and time-consuming isotopic dilution MS (IDMS) method for impurity quantification. Alternative methods that will be investigated include label-free, relative quantification, and standard addition. The project will also evaluate new technologies such as mass photometry, as well as addressing the lack of consensus and guidelines for modified protein measurement (glycoproteins).

Characterisation of the HOS and influence from the primary structure (Objective 2)

MS has emerged as a complementary technique to the traditional protein 3D structure analysis. However, analytical performances of MS for protein structural analysis still need to be documented. This project will go beyond the state of the art by establishing reference protocols for protein measurements that have an estimation of measurement uncertainty. This project will do this to improve the reproducibility and bias of cutting-edge IM-MS and HDX-MS techniques. In addition, where existing software contributes to measurement variability, the project will develop machine learning methods that can detect conformational changes in proteins, in order to overcome this measurement variability.

Characterisation of the protein-protein interactions and influence from the protein structure (Objective 3)

The project will establish a metrological framework for HDX-MS and promote its use for characterising protein-protein interaction. In addition, the project will progress XL-MS measurements beyond the current state of the art towards quantitative methods for differentiating protein conformational states. These advances will then be validated through an interlaboratory comparison.

Influence of protein structure, and interactions on protein measurement and protein function and modelling for measurand definition and uncertainty estimation (Objective 4)

Using input from Objectives 1 to 3 and the development of innovative in vitro assays for determining protein function, this project will advance the state-of-the-art by developing mathematical correlations between protein structure and protein function. This integrative and holistic approach will combine multiple techniques with a metrology framework to enable estimation of the measurement uncertainty. These results can then be used to address the fundamental question of how the quantity of a protein can be best described. The results will also be used to develop guidelines to better define protein measurands, analytical targets and how to estimate measurement uncertainty.

Outcomes and impact

Outcomes for industrial and other user communities

This project will support the industrial end-users to:

- refine and target relevant measurands and analytical entities for protein analysis,
- implement metrological traceability for protein measurements and derive their measurement uncertainty,

- improve the quality of their products (e.g. new measurement technologies or instruments, highly characterised materials).

The project will develop analytical and metrological tools for protein analysis, particularly new RMPs for protein characterisation, and will produce guidelines to support the definition of protein measurands, analytical targets, and their associated measurement uncertainty.

The manufacturers of quality control (QC) / RMs or new protein drugs will particularly benefit from this project's SI traceable metrology framework for the purity assessment of proteins. The project's accurate and improved methods will also be a significant step forward for biopharmaceutical industries as they need the ability to control and validate bioproducts throughout development and manufacturing. Furthermore, through the biopharma industry the project will provide input and support to the currently used guidelines e.g. the International Council for Harmonisation (ICH) Q6B Specifications: test procedures and acceptance criteria for biotechnological/biological products - Scientific guideline.

The lack of suitable primary calibrators traceable to the SI is one of the main obstacles for the food and clinical industries to achieve comparable and reliable results. Providing full SI traceability for protein analysis, including a better understanding of the influence of biological and structural variations on protein measurements, will enable industries to improve their methods and provide clearly defined calibration materials to the end-users.

The project will engage with stakeholders from such industrial and biopharma communities via the setup of a stakeholder network. The stakeholder network will be used to gain feedback on the project and to help maximise impact (project promotion) and to facilitate the uptake of the project's outputs.

The results of the project will also be provided to EURAMET's EMNs on Traceability in Laboratory Medicine and on Safe and Sustainable Food, so that they can be promoted widely to their stakeholders in the Health and Food industries.

Outcomes for the metrology and scientific communities

The expected developments from this project (e.g. the characterisation of the protein structure in biological systems, purity assessment of large and modified proteins, and the evaluation of new calibration strategies for RMPs) are align with the current work of the Protein Analysis Working Group (PAWG) of the Consultative Committee for Amount of Substance (CCQM). Thus, the project outputs will be disseminated to the PAWG in order to support the expansion of NMIs/DIs capabilities, particularly for protein HOS analysis, and paving the way towards new CCQM comparisons on protein structural analysis.

The project's knowledge of the influence of the protein structures on the protein measurement results, will be used to develop guidelines including recommendations to support the definition of protein measurands, analytical targets, and their associated measurement uncertainty based on verified models. These good practice guidelines will be made available to the scientific community via the project website, the participant's websites and a copy of them will be available in an open access repository. The good practice guidelines will enable the better definition of protein measurands and help to improve RMPs targeting the relevant form(s) of the protein.

During the project, close ties to the EMN on Traceability in Laboratory Medicine and the EMN on Safe and Sustainable Food will be sought so that the outcome of this project can be used in outlining roadmaps and updating the EMN's existing strategic research agendas documents.

Further to this, the project will engage with the metrology and scientific communities via the publication of joint research papers in high impact peer-reviewed journals, through the presentation of the project at conferences and as part of knowledge transfer the project will host three educational workshops, secondments for the consortia and at least two training courses for postgraduates.

Outcomes for relevant standards

By developing a metrology framework with a better description of the protein measurand and strategies to better understand the influence of protein structure on measurement and activity, this project will support end-users to meet regulations and standards (e.g. European Medicines Agency (EMA), U.S. Food and Drug Administration (FDA), French National Agency for the Safety of Medicines and Health Products (ANSM), ISO 17511:2020, European Regulation (EU) 2017/746, European Regulation (EU) No 1169/2011 or ICH) Q6B specifications).

This project will also provide input to ISO standards under revision via ISO/TC 212 WG2 Clinical laboratory testing and in vitro diagnostic test systems - reference systems, which is responsible for ISO 15193 (RMPs) and 15194 (RMs) which are both currently under revision. The project will also disseminate its outputs via technical committees ISO/TC 212 WG3 Clinical laboratory testing and in vitro diagnostic test systems - In vitro diagnostic products that is responsible for ISO 17511, ISO/TC 276 Biotechnology, ISO/TC 229 Nanotechnologies, ISO/TC 334 Reference Materials, ISO/TC 194 Biological and clinical evaluation of medical devices, AFNOR S94C Clinical Laboratory Testing and In Vitro Diagnostic (IVDs), EURAMET Technical Committee of Metrology in Chemistry (TC-MC), International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) Scientific Division (SD), IFCC WG-APOMS (Apolipoproteins by Mass Spectrometry), IFCC WG-BND (Biomarkers of Neurodegenerative Diseases), IFCC WG-PCT (Procalcitonin), IFCC WG-hGH (human Growth Hormone), IFCC WG-HbA2 (Haemoglobin A2), IFCC WG-TNI (cardiac troponin I), IFCC WG-NP (Natriuretic Peptides), IFCC C-BM (Bone markers), Joint Committee for Traceability in Laboratory Medicine (JCTLM) Working Group for Traceability: Education and Promotion (WG-TEP), JCTLM Task Force on Reference Measurement System Implementation (JCTLM-TF-RMSI), JCTLM Task Force on Nomenclature, Clinical and Laboratory Standards Institute (CLSI) CLSI EP32 on Metrological Traceability and Its Implementation, Versailles Project on Advanced Materials and Standards (VAMAS) TWA-40 Synthetic Biomaterials.

Longer-term economic, social and environmental impacts

In the longer-term the uptake of the methodologies, protocols and guidelines from this project should impact stakeholders from the health, food, biopharma, diagnostic or environmental sectors, and will further improve the health and safety of consumers and citizen, in Europe and beyond. This project will impact European citizens via improved patient health. Although proteoforms can provide valuable information about patient health, their clinical analysis has not yet received much attention, as methods to identify and quantify them accurately are lacking. This project will expand the knowledge of proteoforms and, thus, support manufacturers to refine existing diagnostic or prognostic tests. In addition, this project should contribute to developing new specific tests (precision medicine), to complementing existing tests or to helping to fill in the gaps at an early and curable stage. An improvement in measurement quality should also minimise false negative or false positive results and, thus, help to prevent the repetition of analyses. Which in turn should reduce costs for patients and the healthcare system.

The long-term uptake of the project's analytical and metrological tools for the structural analysis of proteins and their purity assessment will support better reliability and comparability of protein measurements in biopharma. The implementation of characterisation methods in biopharma should also enable quicker and more reliable identification of issues in biomanufacturing (e.g. the presence of impurities causing adverse effects), thus saving time, resources and costs. This will support better access to therapies at lower costs.

This project will help fill the current gap in the availability of primary calibrators traceable to the SI for accurate allergen detection and biotoxin quantification in the food sector. Furthermore, the availability of reliable methods will help to establish higher quality, robust data in both industrial and fraud control laboratories and support well-informed choices for establishing safety thresholds. All this will help to improve the safety of the food chain and increase consumer protection.

In the fight against doping, this project's outputs will benefit the development of new materials for calibrating doping assays and will support the structural characterisation of different sources of the same doping substance. The advanced characterisation tools that this project will provide will support doping laboratories to demonstrate their ability to meet criteria validated by the Anti-Doping Agencies.



Finally, in the environment, protein analysis is mainly done for total protein content or identification. In line with the One-Health concept supported by Europe, this project will support long-term environmental applications with procedures to identify and quantify proteins reliably.

List of publications

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Project start date and duration:		1 September 2024, 36 months	
Coordinator: Dr Amandine Bœuf, LNE		Tel: 00 33 (0) 1 40 43 39 21	E-mail: amandine.boeuf@lne.fr
Project website address: -			
Internal Beneficiaries: 1. LNE, France 2. BAM, Germany 3. INRIM, Italy 4. PTB, Germany 5. TUBITAK, Türkiye		External Beneficiaries: 6. CNR, Italy 7. CNRS, France 8. GUF, Germany 9. LUMC, Netherlands	Unfunded Beneficiaries: -
Associated Partners: 10. LGC, United Kingdom 11. MHRA, United Kingdom 12. NPL, United Kingdom 13. UCL, United Kingdom			



Publishable Summary for 23FUN07 QuAHMET

Quantum anomalous Hall effect materials and devices for metrology

Overview

The Quantum Hall effect (QHE) is the foundation for the realisation of the primary resistance standard (PRS), representing the “gold standard” in electrical metrology. QHE devices currently require low temperatures and high magnetic fields, impeding their adoption beyond national metrology institutes. The Quantum Anomalous Hall effect (QAHE) provides an opportunity to overcome these limitations while maintaining the unsurpassed accuracy expected of PRS. Greater knowledge of QAHE devices is essential to accelerate the development of a ‘quantum electrical metrology toolbox’ for the universal adoption of quantum electrical SI standards. This project will grow, characterise, and evaluate thin films for QAHE and devices fabricated from them, leading to a detailed metrological assessment from sub-K to above 1 K, currents from below 100 nA to above 1 μ A and over a wide range of external magnetic fields up to several Tesla.

Need

QHE with parts-per-billion resistance quantisation accuracy represents the “gold standard” of primary resistance standards in electrical metrology. However, the QHE devices based on a two-dimensional electron gas at the interface of a gallium arsenide heterostructure impose difficult conditions, i.e., < 1.5 K temperature, > 10 Tesla magnetic field and are limited to a few tens of μ A current, making their universal adoption challenging. The advent of graphene-based Quantum Hall Resistance devices has relaxed the temperature and magnetic field requirements, specifically 4.2 K temperature, 4-5 Tesla magnetic field. However, current research and development work into epitaxial graphene promises only incremental improvements. It fails to address the need for operation at smaller (down to zero) external magnetic fields, and the ease of fabrication into large-area device geometries.

Discovery of topological quantum materials enables the realisation of the so-called quantum anomalous Hall effect (QAHE), i.e. the quantum Hall effect at zero magnetic field, and QAHE devices based on magnetically doped topological insulators are being assessed for their exploitation towards possible applications. However, limitations with respect to operating current and temperature need to be overcome, which are to be addressed in this project by optimised growth of the film materials (Objective 1). Furthermore, this project will investigate novel material systems besides magnetically doped topological insulators and advanced device concepts to explore and achieve the desired electrical transport characteristics and operational margins regarding temperature and current (Objective 1). This requires investigating the electronic, structural, magnetic, and magneto-electronic properties of both magnetically doped topological insulators and novel materials and their devices (Objective 2). The project will also investigate the produced films and devices by surface sensitive techniques and will characterise their magnetic and structural properties using state-of-the-art X-ray, and neutron investigations for a deeper understanding of material/device behaviour for academia and metrology community (Objective 3). In any case, the fabrication of film materials with areas sufficiently large enough to structure them into functional quantum Hall devices is a main aspect of the developments towards novel primary resistance standards that are highly attractive for applications in metrology (Objective 4).

Further improving the primary resistance standard operating conditions will usher in the development of the ‘*quantum electrical metrology toolbox*’ for near-universal adoption of quantum electrical SI standards at NMIs, industrial end users, and calibration laboratories. This project will explore, understand, and implement a new but scientifically grounded methodology for developing metrology grade QAHE devices with relatively larger geometries that achieve resistance quantisation at zero magnetic field, above 1 K temperature and with

Report Status:
PU – Public, fully open

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European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

currents greater than 1 μA (Objective 2). The project's proposed new QAHE-based primary resistance standards will reduce the economic and organisational effort needed to disseminate the electrical units to end users and industries, allowing the installation and maintenance of turn-key experimental systems directly in industry and calibration laboratories, continuously supported and trained by NMIs. This project aims to cover all technology readiness TRLs related to fundamental research (TRL 1 – basic principles observed, TRL 2 – technology concept formulated, TRL 3 – experimental proof of concept and TRL 4 – technology validated in lab), it is therefore expected that the project's results will allow this novel class of materials, devices and PRS to transition from the laboratory to larger TRLs.

Objectives

The overall aim of the project is to introduce traceable measurements on and characterisation of quantum anomalous Hall effect (QAHE) materials and devices as primary resistance standard candidates.

The specific objectives are:

1. To improve the growth of magnetically doped topological insulator (TI), (e.g., vanadium doped Bi_2Te_3 and Sb_2Te_3) thin film samples by molecular beam epitaxy on closely lattice matched substrates. Furthermore, to explore the effects of anisotropic magnetic insulator layers (e.g. BST/RE-BST on magnetic insulators) interfaced with TIs and to produce high structural quality materials (Kagome magnets, V-BST on magnetic insulators) with properties optimised for the QAHE.
2. To investigate the bulk electronic, structural, magnetic, and magneto-electronic properties of the QAHE films and devices produced in Objective 1 under various temperatures (from below 50 mK up to 300 K), currents (from below 100 nA to over 1 μA) and applied magnetic fields (from 0 T to 10 T) for different growth conditions. In addition, to investigate the limitations of QAHE, i.e., low critical temperatures and currents when working on precision growth-control of interfaces.
3. To investigate fabricated QAHE thin films and devices produced in Objective 1 by surface sensitive scanning probes (SPM) and magnetometry techniques (e.g. Scanning SQUID, SMM, scanning SNOM) at low temperatures (from below 50 mK to 300 K), and to characterise their magnetic and structural properties using X-ray, and neutron investigations.
4. To develop and carry out detailed metrological assessments of QAHE devices (e.g. V-BST) using several techniques (e.g. CCC, impedance bridge), both at sub-Kelvin and above 1 K temperatures, aiming at QAHE resistance quantisation accuracy between 1 and 10 ppm, above 1 K, at currents above 1 μA and at low-to-zero applied magnetic field. In addition, to write a good practice guide on the use of the QAHE devices for resistance metrology.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by standards developing organisations (BIPM), end users interested in applications, such as spintronics and topological quantum computing and advance the research and progress in the field of TIs.

Progress beyond the state of the art and results

This project aims to understand and demonstrate the metrological applicability of QAHE materials and devices by using the most advanced magneto-transport, scanning probe and large-scale X-ray synchrotron and neutron facilities across Europe, as well as metrologically accurate measurement systems for evaluating the quantum Hall resistance of test samples.

Objective 1: Improving the growth of magnetically doped topological insulator (TI), (e.g., Bi_2Te_3 and Sb_2Te_3) thin film samples and investigating the effects of anisotropic magnetic insulator layers interfaced with TIs

Chromium (Cr) and vanadium (V) doped $(\text{Bi}_x\text{Sb}_{1-x})_2\text{Te}_3$ (BST) materials are the most actively explored and optimised systems where QAHE has been demonstrated. However, QAHE still requires milli-Kelvin (mK) operating temperatures. In this project, metrologically relevant vanadium (V) doped BST (VBST) materials will be realised, and existing knowledge on why devices demonstrate QAHE only in the mK temperature range and below 1 μA current and not at higher temperatures and currents will be extended.

In this project, two additional materials pathways will be explored for elevated temperature QAHE: (i) magnetic proximity effect materials with magnetically doped or pristine BST topological insulators (TIs) grown on top of

known anisotropic magnetic insulators (MIs); and (ii) Kagome magnets which intrinsically combine topology and magnetism and are considered excellent platforms.

Multiple research groups have demonstrated enormous anomalous Hall effects for both these materials pathways; however, quantisation has been lacking. In this project, the magnetic proximity effect utilising both pristine and doped BSTs with 3d-transition or lanthanide elements will be investigated. Meanwhile, various magnetic Weyl semimetals will be investigated for Kagome magnets. Additionally, this project aims to demonstrate QAHE with good resistance quantisation accuracy.

Objective 2: To investigate the electronic, structural, magnetic, and magneto-electronic properties of the fabricated samples by using QAHE devices

Certain properties of VBST have previously been studied. However, focused efforts targeting the application of such materials for the next generation of resistance standards by multiple European national metrology institutes is a first-of-its-kind effort. In this project, efforts will be made to complement traditional materials with novel ones by bridging material physics and metrology.

Objective 3: To investigate fabricated samples by scanning probes and magnetometry techniques

Functional scanning probe microscopy (SPM) will inform understanding of QAHE materials with the possibility of imaging edge states, bulk and edge currents, magnetic domains and their dynamics and understanding the effects of film thickness on hybridisation of electronic states. In particular, one of the world's first cryogenic scattering-type scanning nearfield optical microscopes coupled with light sources ranging from visible, mid-infrared to terahertz will be used to enable nanoscale optical and optoelectronic imaging and spectroscopy of the surface and the bulk electronic states of TI samples. Scanning SQUID microscopy will be carried out using state-of-the-art SQUID-on-lever probes to map both magnetisation and current density. These probes, which can operate in applied fields as high as 1 T, are unique in that they combine high magnetic flux sensitivity and high spatial resolution below 100 nm with the topographic contrast provided by atomic force microscopy.

Objective 4: To develop and carry out a detailed metrological assessment of optimised QAHE devices

At the European level, PTB with University of Würzburg have demonstrated the world's most precise quantisation value using vanadium BST without a magnetic field. Beyond Europe, both NIST and AIST have performed an initial metrological assessment of QAHE with uncertainties down to a few parts in 10^8 . This project envisions substantially higher precision quantisation tests with improved VBST growth and sample design. First-of-a-kind use of novel topological material classes in this project aims to lay the foundations for future EURAMET QAHE research and development projects.

Outcomes and impact

Outcomes for industrial and other user communities

The top-level goal of this project is to realise primary electrical standards under more relaxed conditions, making SI traceability more accessible to the industry. Accessibility is an essential requirement of the SI system of measurement. Reducing the cost overhead associated with maintaining a primary resistance standard will bring these standards closer to industrial end users, enabling better control of industrial processes (for example, semiconductor manufacturing). A quantum Hall resistance standard operating at zero magnetic field would also enable the realisation of a '*quantum electrical metrology toolbox*' (QHE and Josephson voltage standard integrated in a single package). This would be an unprecedented achievement within quantum electrical metrology – a single, general-purpose primary standard. Via the fan-out effect in the pyramid-like structure of traceability chains from NMIs to millions of measurements and calibrations, European calibration services and industry will benefit from such a development.

In a broader sense, topological materials are particularly attractive for next-generation energy and information applications because many topological effects, including QAHE, are achievable at room temperature due to the inherently protected nature of topological effects to thermal fluctuations. The project will also impact other user communities, including photonics, broadband solar energy harvesting, high power-factor heat recovery and next generation energy storage. The International Roadmap for Devices and Systems from IEEE highlights the QAHE field by considering it as a prospective candidate for future non-volatile cryogenic memory arrays within spin-Hall effect devices for spintronics.

Outcomes for the metrology and scientific communities

Both topological insulators and QAHE are vital research fields. However, they are still young, with the QAHE demonstrated only 10 years ago. The core impact of the work is dual, both metrological and scientific in nature. Scientific impact includes a spectroscopic understanding of topological insulators, Kagome magnets and magnetic proximity effect materials and a deeper understanding of the electronic, magnetic, and structural landscape of QAHE heterostructures through diffraction and magneto-transport measurements. Scanning probe techniques will provide insight into thin film growth quality and act as feedback for quality control parameters. The QAHE in TIs offers several other exciting applications in topological quantum computing, low-power electronics IoT, neuromorphic computing and spintronics. At the same time, metrological impact focuses on harnessing the exotic condensed matter phenomenon of QAHE, where low-to-zero magnetic fields permit the '*relaxed conditions*' requirement for realising a future '*quantum electrical metrology toolbox*'. Similar efforts to miniaturise and integrate atomic clocks have led to its unprecedented spread, especially in the field of quantum computing.

As scientific and metrology communities embrace topical developments in the field of quantum technologies, topological materials will play an important role in the quantum materials front for the realisation of new standards based on precisely quantised phenomena, such as quantum conductance, QAHE, the quantum spin Hall effect and fractional quantum Hall effect, just to name a few. This outlines the need for NMIs to become active and core contributors to such research and development efforts on the QAHE, as indicated by the strategic research agenda of the European Metrology Network for Quantum Technologies (EMN-Q). The consortium will take advantage of distinct NMIs that have gained significant expertise in the related and relevant research fields demanding highly advanced measurement capabilities like those required for QAHE research.

This project will further provide an understanding of how these fundamental quantum phenomena can be practically implemented to develop new metrology standards. Not least, this will involve implementing and improving the growth of TI and magnetic TI layers and interfaces not limited to just the BST family but investigating emerging QAHE candidates such as Kagome magnets and magnetic proximity effect materials using magnetic insulators which promise to operate at more moderate temperatures, and which are more universally accessible to broader scientific and metrology communities.

Outcomes for relevant standards

Development of QAHE based resistance standards will have an immediate impact on the future of quantum Hall resistance standards. Relevant committees are expected to be highly supportive of developing science, technologies, measurement techniques and instrumentations from this project and will be kept informed of the progress made. This consortium maintains memberships in several standardisation and technical committees and will ensure early uptake of the project's results in relevant standards documentation. The project will be represented in key European committees related to electrical metrology, such as the EURAMET Technical Committee on Electricity and Magnetism (TC-EM), the CCEM Working Group on Low-Frequency Quantities (WGLF), and the TC-EM subcommittee on DC and Quantum Metrology (SC-DCQM). Beyond Europe, international committees such as IMEKO TC-4, COOMET TC 1.3 on Electricity and Magnetism, GULFMET TC-EMFT and the Asia Pacific Metrology Programme (APMP) will be addressed.

Longer-term economic, social, and environmental impacts

The realisation and dissemination of the electrical units should be robust against foreseen economic and environmental trends. Currently, the use of the QHE as a primary standard is threatened by the rising cost of energy and cryogenic cooling, as well as the rarity of materials used to manufacture superconducting magnets. This project aims to future-proof the top-level realisation of the electrical resistance units by developing QHE devices which do not require magnets or extensive cooling. Such a development would also make primary SI traceability more accessible to NMIs in low- and middle-income countries, technology industries and calibration laboratories, bringing primary standards closer to the end user. This will position European metrology in a prime position to not only contribute to development of the next-generation of QHR standards, but also be a part of developing excellent science towards advanced applications in spintronics, low-power electronics and topological quantum computing. Furthermore, corresponding efforts will make European NMIs early adopters of such technologies, to become providers of scientific expertise to other NMIs world-wide. This project introduces the first such coordinated effort from European NMIs on the topic of QAHE using topological insulators.

List of publications

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months
Coordinator: Susmit Kumar, JV Tel: +47 64 84 84 87		E-mail: sku@justervesenet.no
Project website address: https://sites.google.com/inrim.it/quahmet/home		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. JV, Norway	6. JMU, Germany	8. TAU, Finland
2. CMI, Czechia	7. Koc, Türkiye	9. UNILE, Italy
3. INRIM, Italy		
4. PTB, Germany		
5. TUBITAK, Türkiye		
Associated Partners:		
10. AIST, Japan		
11. METAS, Switzerland		
12. NPL, United Kingdom		
13. UNIBAS, Switzerland		
14. UOXF, United Kingdom		

Publishable Summary for 23FUN08 MetSuperQ Metrology for superconducting qubits

Overview

Superconducting circuits are a leading technology for the realisation of practical quantum computers. However, scaling-up towards full-scale, fault-tolerant quantum computers will involve addressing many challenges concerning, e.g., qubit coherence, reproducibility, stability, cross-talk, control, and readout. In order to achieve this, a new generation of metrological methods and tools will be needed. This project will develop such a suite of tools for superconducting qubits and apply them to state-of-the-art one- and two-qubit circuits. These new tools will underpin further engineering advances and allow for accurate characterisation of qubits and materials, as well as manipulation and read-out.

Need

A qubit is regarded as the basic unit of information in quantum computing and a counterpart to the bit (binary digit) in classical computing. In recent years quantum computing has become one of the hottest research topics worldwide. Yet, despite many advancements, qubits are still too faulty to be used for practical quantum computers and this situation is referred to as the Noisy Intermediate Scale Quantum (NISQ) era. Many obstacles remain towards a practical fault-tolerant, i.e., error-corrected, quantum computer (FTQC) capable of solving computational problems far beyond today's classical capabilities, impacting a broad range of sectors.

To reach beyond today's NISQ computers measurement methodology and accuracy need to be improved - this is a key objective of MetSuperQ. With improved measurements for superconducting qubits and peripheral devices comes the ability to distinguish, and accurately quantify the contributions of the plethora of different decoherence mechanisms arising from the materials, circuits, and devices, that degrade the performance of quantum computers. This will directly trigger advances in engineering, hardware, and materials aimed towards improved coherence and scalability. National (NMI-level) capabilities are required that can support commercial efforts, accelerate commercialisation in the field and bring European capabilities reaching beyond the present NISQ-era.

More specifically, there is discrepancy regarding how superconducting qubit metrics are reported in the literature and by companies, which makes comparison of parameters and performance difficult. Current performance metrics potentially mask key decoherence-limiting physical mechanisms, and in order for these to be addressed significant improvements to materials, readout and control electronics, and circuit design are required. Both measurement methodologies and analysis routines need harmonisation. Such harmonisation requires a large number of institutions to work together to develop techniques that are applicable to a wide range of conditions, and to conduct laboratory Round Robin comparisons using different hardware setups that subject superconducting circuits to a wide range of conditions.

Objectives

The main goal of this project is to develop novel metrology tools for superconducting qubits, to support the development of superconducting quantum computers. The specific objectives are:

1. Qubit materials: To investigate new ways of characterising materials of superconducting qubits, to be used for qubit metrology, at temperatures below 1 K. To explore different high-coherence materials and processing steps to facilitate comparisons of material measurement techniques. To

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European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

develop standardised design and processing procedures for interlaboratory comparisons and reproducibility tests of material measurement techniques.

2. Qubit periphery: To develop, fabricate, and test peripheral devices, such as parametric amplifiers and quantum-accurate Josephson pulse generators, to perform qubit control and read-out operations. To mitigate uncertainties arising from peripheral devices used in the control and read-out chain.
3. Metrology for single and two-qubit gates: To develop harmonised qubit characterisation routines to unpick mechanisms limiting scalability, coherence, and fidelity. To develop statistical tools for accurate benchmarking with minimised measurement error and overhead.
4. Round Robin: To perform a first Europe-wide Round Robin on basic parameters of single qubits. To develop and validate measurement protocols and recommendations for reproducible characterisation of single qubits, including a best practice guide.
5. Impact: To facilitate the take up of the technology and measurement methods developed in the project by the industrial stakeholders and others, and to engage with industrial stakeholders to understand how to support their future needs for superconducting qubit metrology. To implement a research network to enhance collaboration and to create characterisation abilities for superconducting qubits among European NMIs. To engage standardisation bodies (e.g. CEN-CENELEC) to identify standardisation needs for superconducting qubits and to initiate corresponding standardisation activities.

Progress beyond the state of the art and results

So far, no superconducting qubit metrology exists worldwide, and MetSuperQ will enter this new metrology area. By the end of the project understanding of decoherence mechanisms in devices and materials that limit scalability of superconducting quantum computers will have been advanced. The project will specifically target results advancing state of the art and gaining new fundamental insights in the following areas:

Qubit materials (Objective 1)

All state-of-the-art superconducting qubits are made using Aluminium/Aluminium-Oxide/Aluminium Josephson junctions with the rest of the circuitry being made either from Aluminium, Niobium or Niobium-Nitride. Qubit devices fabricated from a variety of materials, including Aluminium, Niobium, Tantalum and other, higher-T_c superconductors, will be evaluated aimed at better understanding the advantages of individual materials. A range of new characterisation techniques, including low temperature scanning probe microscopy and analysis techniques for in-situ material and device characterisation, will be specifically designed and implemented. Knowledge will be improved of the factors limiting the coherence of state-of-the-art superconducting qubit chips (including two-level systems, flux noise, quasiparticles, infrared radiation, control and readout) and how to mitigate them. Standardised device designs will be produced for comparisons and studies on the effects of materials, design parameters, and processing steps on qubit coherence. In addition, new fabrication techniques and materials for qubits with increased coherence and characterisation of their dominant residual decoherence mechanisms will be developed.

Qubit periphery (Objective 2)

The overall superconducting quantum computing system capability is not only limited by the qubit coherence time, but also by the control and read-out electronics, and interconnections. In the project, quantum-limited parametric amplifiers and quantum-accurate cryogenic waveform generators will be developed, benchmarked, and integrated with qubit readout/control. Moreover, component-based and full system characterisation will be compared to each other. Josephson pulse generators and optimised pulse patterns will be utilised to reduce qubit gate times towards greater circuit depth execution and scalability.

Metrology for single and two-qubit gates (Objective 3)

A range of different sample devices designed to be limited by different decoherence mechanisms (TLS, quasiparticles, etc.) will be investigated. Harmonised measurement and analysis routines (including public, modular and futureproof framework) for fast and accurate benchmarking of superconducting qubits will be developed, as well as methods to speed up qubit benchmarking. The benchmarking and analysis routines developed will go beyond the current state of the art in accuracy of deducing the 'decoherence budget' of qubits and determining factors limiting scalability.

Europe-wide Round Robin on basic parameters of single qubits (Objective 4)

Utilising developments earlier in the project, a Round Robin comparison will be performed demonstrating qubit benchmarking at multiple NMIs and laboratory settings capable of disentangling intrinsic (package level) from external (laboratory, electronics) sources of decoherence. This European comparison will bring several NMIs and other institutes into alignment to be able to deliver state of the art measurement capabilities for superconducting circuits and will form a European counterpart to US activities.

Progress beyond 20FUN07 SuperQuant

To obtain these insights and successfully reach the objectives, input from 20FUN07 SuperQuant will be required with respect to Josephson pulse generators working at GHz frequencies and microwave metrology in cryogenic environments. Yet, it is important to emphasize that SuperQuant does not address metrology of superconducting qubits and, thus, MetSuperQ will significantly go beyond SuperQuant.

It is expected that the project's results will lead to a large number of high impact journal publications with joint authors from different countries across this whole range of activities, in addition to new tools, measurement protocols and circuits with enhanced performance compared to today's state of art. In the addition to the scientific and metrological results, the NMI participants will investigate the possibility for new measurement services or capabilities for qubit materials, parametric amplifiers, and qubits.

Outcomes and impact

Outcomes for industrial and other user communities

American enterprises are currently industry leaders in the development of superconducting quantum computers, but there are a number of important and growing European SMEs focusing on both hardware- and software development. Additionally, there is also a growing European supply chain with companies producing, for example, instrumentation, parametric amplifiers, RF-components, and cryogenic systems needed to build superconducting quantum computers.

The outputs from the project, e.g., improved fabrication techniques to reduce decoherence and other defects in materials, optimised drives for superconducting qubits to reduce qubit gate times, processes for fast and accurate benchmarking of qubit parameters and state preparation, tools for improved statistical analysis of qubit temporal data, and a best practice guide, will further underpin development of the industry in Europe. Access to accurate information about the parameters of qubits, as well as good metrics that enable comparison of parameters, devices, and performance is increasingly important not only for quantum computing hardware manufacturers, but also to the wider supply chain as well as end-users and potential investors in quantum computing. The capability created in MetSuperQ among European NMIs for accurate measurement of superconducting qubits and the novel methods and best practises established will help to meet the metrology challenges in this emerging field. The tools developed in this project will also be relevant to other areas using related superconducting- and cryogenic technologies, such as test and measurement, telecommunications, microwave components, space and military communications systems, cryogenic systems, and medical imaging. The generated IP will be offered for exploitation to European stakeholders to increase the competitiveness of the European quantum industry.

The project will help create awareness in the community about the importance of metrology, best-practice and comparisons for achieving precise, trusted measurements, for example through the publication of peer-reviewed papers, the good practice guide, a workshop, and liaison with relevant networks and consortia such as the European Metrology Network for quantum technology (EMN-Q), the European Quantum Industry Consortium (QuIC), and the Quantum Economic Development Consortium (QED-C).

Outcomes for the metrology and scientific communities

The project will enable the participating NMIs to enhance their ability to support leading European quantum technology and computing hardware- and software companies as well as the supply chain with enhanced measurements and future standards. No NMI currently has the capabilities required to carry out all aspects of establishing this capability alone, so the collaborative effort among several NMIs and leading research groups in MetSuperQ will help fully exploit and disseminate the outcomes of this opportunity. The results and outputs of MetSuperQ will lead the way to the worldwide first calibration services for parametric amplifiers and superconducting qubits.

International comparisons, i.e., Round Robins, are essential prerequisites for obtaining confidence in measurements. The first Round Robin on qubits in Europe performed in MetSuperQ will establish a European counterpart to a US initiative and can be considered to be a very important milestone for qubit measurements in Europe. The protocol for the Round Robin will be converted into a Best Practice Guide, which will be disseminated to international stakeholders.

In addition to metrology aspects MetSuperQ also addresses cutting-edge quantum technology projects in Europe within the EU quantum flagship, Horizon Europe and Horizon 2020 programmes. MetSuperQ participants also participating in these projects will profit from mutual synergy effects and contribute to the growing together of the European science community on superconducting quantum technology.

Outcomes for relevant standards

Several standardisation development organisations (SDOs) have already initiated activities in the area addressed by this project, including, for example, IEC and CEN/CENELEC (via the new JTC22). European NMIs are already actively participating in these standardisation activities. Based on the roadmaps already created within CEN/CENELEC (via JTC 22) with participation from participants of MetSuperQ, it is expected that standards for basic metrics for qubits and quantum processors will be an early area of interest for standards development. Standardised benchmarks and metrics for the current generation of quantum processors are also under discussion within other organisations such as IEEE, QED-C and QuIC. All these efforts will require the relevant metrology and best practices to be developed.

Longer-term economic, social and environmental impacts

The quantum computing market is projected to grow rapidly within the next decades. Significant economic impact will occur through the development of new products. The value-added growth due to the use of quantum computers could be between \$600 billion and \$1300 billion in 2035. Europe urgently needs to invest in quantum technology to be able to keep pace with the US and China. Metrology developed within the MetSuperQ project will support the European quantum technology and quantum computing industries, since metrology tools are needed to realise and scale up practical quantum computers.

Computing with significantly more than 10^{18} floating point operations per second will require new computational schemes offering improvement in flops per watt over the technology available today. Superconducting quantum computing is one of the technologies, which might be able to reach this goal. This also has significant economic impact, as data centres are foreseen to have an energy consumption of up to 8000 TWh in 2030, thus a 10 % energy saving of such devices, i.e., 800 TWh per year, would directly result in about €240 billion financial savings.

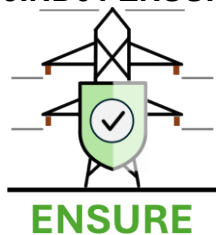
In the long-term society needs technologies based on innovative products and concepts. Quantum computing has the potential to disruptively improve our daily life through the realisation of orders-of-magnitude-improved computational speed. Superconducting circuits are a leading technology for the realisation of such quantum computers. As quantum computers continue to be scaled up, the need for associated metrology will continue to grow.

The MetSuperQ project may also have environmental impact if it helps to contribute to solving the unsustainable growth of energy consumption of ICT equipment. The European Green Deal aims to create the first climate-neutral continent. The above-mentioned energy saving of data centres could be used to shut down more than 90 medium-sized coal-fired power plants and, thus, considerably decarbonising the energy sector.

List of publications

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months
Coordinator: Mark Bieler, PTB Tel: +49 531 592 2400 E-mail: mark.bieler@ptb.de Project website address: ---		
Internal Beneficiaries: 1. PTB, Germany 2. DFM, Denmark 3. INRIM, Italy 4. JV, Norway 5. LNE, France 6. VTT, Finland	External Beneficiaries: 7. KIT, Germany 8. KU, Denmark 9. Orange QS, Netherlands	Unfunded Beneficiaries: =
Associated Partners: 10. ETHZ, Switzerland 11. METAS, Switzerland 12. NPL, United Kingdom 13. UNIBAS, Switzerland		



Publishable Summary for 23IND01 ENSURE

Electric energy and supply reliability

Overview

The amount of electricity generated from renewable sources needs to increase to meet the EU's aim of becoming carbon neutral by 2050. However, the connection of renewable sources to the power grid causes harmonics which lower network power quality and increase electricity losses in e.g., power transformers and high-voltage alternating current (HVAC) cables. The industry thus requires new HV metrology tools to monitor the increased level of grid harmonics, as well as instrumentation to quantify the impact of these harmonics on the efficiency of power transformers and HV cables, plus new methods to evaluate the reliability of high-voltage direct current (HVDC) grid connections. Therefore, this project will develop new 1) wideband live connectable current or voltage sensors to monitor and calibrate substation instrumentation, 2) capabilities for determining the power transformer losses that are caused by grid harmonics, 3) methods for determining harmonic losses from HVAC cables, and 4) partial discharge (PD) monitoring techniques for fault detection and location in HVDC cables.

Need

In the ongoing expansion of HV power grids, new power sources from renewables, wind, solar and battery power have been introduced. These sources use converters/inverters for interfacing to the grid, which pollutes it with harmonics. Harmonics will inevitably lead to increased losses in power transformers, especially in the older types, as well as in both overhead power lines and underground cables in the HV grid. Power transformers of older types are not designed to transmit harmonics leading to excess losses and overloading. There is therefore a need for new metrology to determine the impact of harmonics on these excess losses.

HV cables are used for new overseas interties, for the replacement of existing land-based overhead lines or they are selected for bulk transmission in Europe, e.g., in Germany for transmitting electricity from the wind farms in the Baltic Sea to Bavaria. Losses from harmonics need to be minimised so that they do not overload the interties, for example there are cases where HVDC interties from Sweden were overloaded by harmonics from a rectifier.

Furthermore, HV grid operation needs new reference instrumentation both for the calibration of instrumentation in substations and for the monitoring of harmonics, in order to ensure stability and reliability in the presence of the steadily growing portion of renewable electricity, which is entering the grid. In particular, old substations need to be updated to enable the measurement and monitoring of power quality. New metrological solutions for the monitoring of harmonics will be needed if energy stores are used to compensate for the losses of grid inertia and for the reduction of harmonics.

HV grid condition monitoring is crucial to ensure the reliability of the electricity grid. There is a strong industrial need for applying new partial discharge (PD) detection that will work at up to 30 MHz. Such a development is in particular relevant for monitoring HVDC systems. The EMPIR JRP 19ENG02 FutureEnergy improved the understanding of PD behaviour under DC stress, highlighting the need for voltage changes to trigger PD in HVDC grids. Building on these insights, the primary need is to further study PD behaviour during sudden

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by
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Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

voltage changes, including transients (e.g., lightning impulses and pole to ground faults at converter stations) and harmonics.

Objectives

This project focuses on the metrology research necessary to support standardisation and the development of traceable tools for HV condition monitoring and fault detection as well as the means to ensure the reliable determination of losses in HV transformers and HV cables.

The specific objectives are:

1. To perform on-site calibration of instrument transformers in substations with minimised downtime or even live connection with reference instrumentation based on e.g., optical current sensors. To use these sensors to upgrade/retrofit existing instrument transformers for use in higher harmonics measurements, and power quality monitoring. Target measurement uncertainty 0.05 % (of fundamental) for currents up to at least 1 kA at fundamental tone and 0.5 % in the harmonic range.
2. To develop reference instrumentation with a bandwidth of at least 2 kHz for the determination of the impact of grid harmonics on power transformer losses with a target uncertainty of better than 1 % of the loss power. To realise a HV capacitor reference for loss factor determination up to 30 kV with an uncertainty of 5 ppm at power line frequencies (50 Hz - 60 Hz) and 20 ppm at 2 kHz.
3. To develop new traceable metrology for the determination of the skin effect of HVAC cables using both calorimetric and electrical methods up to 3 kA with a 2 % and 1 % uncertainty respectively, including a study of the effect of harmonic currents. To demonstrate the new method on two samples from cable manufacturers.
4. To develop new measurement capabilities for PD measurements in DC cables at 100 kV and above for use in monitoring systems for the detection, classification and localisation of defects or damage before breakdown. To demonstrate the new method on at least two samples of HVDC cable with known defects (provided by an industrial participant).
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by standards developing organisations (CENELEC/IEC TC14 "Power transformers", CENELEC/IEC TC38 "Instrument Transformers", EURAMET TC Electricity and Magnetism and IEC TC42 "High-voltage and high-current test techniques"), by the EMN for Smart Electricity Grids and end users (e.g. manufacturers and network operators).

Progress beyond the state of the art and results

This project will develop new HV measurement technology in the following four interrelated areas:

To perform on-site calibration of instrument transformers in substations with minimised downtime or even live connection with reference instrumentation based on e.g., optical current sensors. To use these sensors to upgrade/retrofit existing instrument transformers for use in higher harmonics measurements, and power quality monitoring. Target measurement uncertainty 0.05 % (of fundamental) for currents up to at least 1 kA at fundamental tone and 0.5 % in the harmonic range. (objective 1)

Starting from the proof-of-concept fibre optics current sensor (FOCS) developed in EMRP JRP ENG61 Future Grid (Technology Readiness Level (TRL) 3), this project will progress beyond the state of the art by setting up a non-invasive optimised FOCS sensor as a new wideband reference. Alternative non-invasive current sensors will also be selected, and their performance will be demonstrated on-site. The sensors' non-invasive design, and on-site live connection and measurement procedures, will be made available for use during the calibration phase. This will enable the positioning and measurement time to be minimised, and on-site live calibrations will be made possible with target uncertainties of 0.05 % of the fundamental current at up to 1 kA, thus reaching TRL 6. The use of these wideband reference sensors for the upgrading/retrofitting of installed CTs, which are based on old technology, will allow their use to be extended to harmonic measurements and power quality monitoring. Finally, the availability of such reference current sensors, coupled with reference voltage sensors and the associated reliable algorithms, will pave the way for the validation and adoption of the non-invasive wide area remote calibration of instrument transformers.

To develop reference instrumentation with a bandwidth of at least 2 kHz for the determination of the impact of grid harmonics on power transformer losses with a target uncertainty of better than 1 % of the loss power. To realise a HV capacitor reference for loss factor determination up to 30 kV with an uncertainty of 5 ppm at power line frequencies (50 Hz - 60 Hz) and 20 ppm at 2 kHz. (objective 2)

The verification of power transformer losses, in the presence of harmonics, requires systematic research with a traceable measurement system. To get a systematic scientific inspection of the influence of harmonics on power transformer efficiency, the existing reference loss measurement systems need to be extended in frequency beyond the present power line frequencies (50 Hz – 60 Hz) to at least 2 kHz. To this end, the voltage channel, current channel and power analyser must be verified and calibrated before precise harmonic loss measurement is possible. The aim is to reach a target uncertainty in harmonic loss measurement of better than 1 % of the total loss power. To support the traceability of this wideband reference loss measurement system, the present limited traceability in HV capacitor loss factor (only up to 2 kV) will be extended by the development of a HV capacitor reference, for loss factor determination at up to 30 kV, with an uncertainty of 5 ppm. This project will furthermore go beyond the state of the art by training AI models for determining the wideband losses in the magnetic core materials that are used in power transformers. This will be achieved by implementing physics-based data analytics (knowledge aware artificial neural network (KANN)), which will pave the way to fast and accurate overall loss estimations of power transformers for manufacturers.

To develop new traceable metrology for the determination of the skin effect of HVAC cables using both calorimetric and electrical methods up to 3 kA with a 2 % and 1 % uncertainty respectively, including a study of the effect of harmonic currents. To demonstrate the new method on two samples from cable manufacturers. (objective 3)

The techniques for measuring the ratio between the AC and DC resistance of a low loss cable have been established using both electrical and calorimetric measurement systems. This project will go beyond the state of the art for both electrical, and especially calorimetric, methods for skin-effect loss determination in HVAC cables, not only in the presence of the fundamental, but also in presence of harmonics. The new method will be demonstrated on two samples from cable manufacturers. This project aims to significantly improve the measurement uncertainty and the ease of implementation of both the calorimetric method (uncertainty typically 7 %) and the electrical method (uncertainty typically 2 %). The measurement uncertainty target is 2 % for the calorimetric method and 1 % for the electrical method at up to 3 kA.

To develop new measurement capabilities for PD measurements in DC cables at 100 kV and above for use in monitoring systems for the detection, classification and localisation of defects or damage before breakdown. To demonstrate the new method on at least two samples of HVDC cable with known defects (provided by an industrial participant). (objective 4)

This project aims to progress beyond the state of the art by developing innovative techniques for detecting online PD signals within HV cable systems that are subjected to sudden voltage changes like transients (e.g., lightning impulses, pole-to-ground faults at converter stations), and harmonics. It seeks to establish a reliable method for online PD monitoring (for the detection, classification and localisation of defects or damage before breakdown) in HVDC grids at 100 kV and above, which will be able to distinguish PD from transient noise. The new method will be demonstrated on at least two samples of HVDC cable with known defects. This advancement is vital for both promoting competitiveness in the European industry and ensuring the reliability of existing HVDC infrastructure.

Outcomes and impact

Outcomes for industrial and other user communities

This project will develop a range of new measurement capabilities at the NMIs, aimed to ensure reliable electrical energy supply in the context of increased renewable energy sources (RES) generation. These new capabilities will be of direct relevance to, and will benefit, industrial communities.

The new reference fibre optics current sensor (FOCS) and an associated good practice guide for the calibration of wideband current measurement transformers will be particularly relevant for utilities (TSOs and DSOs) and grid instrumentation manufacturers. It will support the power industry in developing new instrument transformers that can be used to measure and monitor the increased load from harmonics.

The reference instrumentation for the measurement of harmonic losses in power transformers and AC cables will allow TSOs and DSOs to gain insight into the extra losses, and thus the extra cost of ownership, that originates from grid harmonics. The new traceable loss metrology developed in this project will be crucial for utilities to prevent overheating and subsequent failure of HVAC cables and power transformers. Power transformer and cable manufacturers can in turn use the new measurement capabilities for the development and verification of improved, lower-loss, products.

The new PD measurement procedures under HVDC conditions will support PD instrumentation manufacturers in the development of new PD measurement equipment and cable manufacturers in the design of improved DC cables. The good practice guide for the application of the new PD measurement procedures under HVDC will allow utilities, such as REE and TenneT, to classify and localise defects in HVDC cable interconnects.

To facilitate uptake of the project's outputs there will be considerable engagement throughout the project with industrial stakeholders, i.e., manufacturers of high voltage measuring devices, grid system operators and calibration laboratories. The involvement of industrial collaborators (e.g., REE, HIGHVOLT) and the establishment of a Stakeholder Committee will ensure that the project remains aligned with industrial needs. In addition, at least two international workshops aimed at collaborators and stakeholders will be organised by the project for demonstration of the new measurement techniques, where representatives of grid equipment manufacturers, instrumentation manufacturers, standardisation bodies, utilities, universities and NMIs will be invited.

Outcomes for the metrology and scientific communities

The outcomes of this project will include several important additions and extensions to the NMI/DI Calibration and Measurement Capability (CMC) statements in the BIPM key Comparison Database (KCDB), and as such, this will provide a significant impact to the worldwide electrical power metrology community. Specifically, six new and extended CMCs are foreseen.

The harmonic losses of power transformers are a fraction of the losses that occur at power line frequency. This puts extreme phase accuracy requirements on the key components of the reference harmonic loss measurement setup, the voltage and current sensor and the power meter. Therefore, this project aims to create outcomes and impact for the metrological and scientific community by pushing the limits of the wideband phase characterisation of this equipment. The project's research results will be presented by the consortium at scientific and stakeholder conferences and workshops, and they will be published in peer-reviewed journals.

Outcomes for relevant standards

The consortium will promote the project's results and outcomes within the standardisation community, including within IEC and CENELEC, and will provide input into the revision of standards, for example the IEC 63405, IEC TS 62478, IEC 60270 and the IEC 61869 series, via active participation in the technical committees. Furthermore, the power transformer community, participating in the CENELEC TC14 "power transformer" standardisation technical committee, will be updated regularly via their semi-annual meetings. During the project, other relevant standards that are in preparation/revision will be identified, and the project's input to such standards will be suggested to the appropriate working groups or committees.

Longer-term economic, social and environmental impacts

The research in this project will directly stimulate innovation and it will impact the competitiveness of the European HV manufacturing and test industry by providing them with traceability for unambiguous determination of the quality of their products. Harmonic loss will be systematically studied during this project, and it will provide industrial manufacturers with insight into the possible factors and influences. The overall benefit of the project to industry and distribution and transmission system operators is evident from the involvement of stakeholders. The strong participation of research institutes and universities in the project will ensure the long-term dissemination of the results within the high voltage community. All this will lead to more efficient and reliable, and more affordable, future power grids.

This project offers a unique opportunity for European NMIs to pool their collective strengths, and unique capabilities and facilities, to make an impact by improving future grids. The research will provide the required tools, methods and facilities for a robust realisation of the future grids. Blackouts such as recently experienced in South America would have an enormous impact on our advanced European society, and efforts are needed to avoid a comparable situation in Europe.

The current 300 TWh/year losses in European transmission grids correspond to an astonishing emission of 150 000 000 tons of CO₂ per year. Supporting our understanding of the influence of harmonic losses, will enable grid losses to be reduced. Even the smallest contribution to this improvement will result in a major reduction, of many kilotons per year, in the CO₂ emissions caused by electricity transmission. The study of PD behaviour in HVDC transmission cables, and the application of the fault location techniques under development will lead to more reliable transmission cable connection in the future electrical power grid.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months
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Project website address: https://www.epm-ensure.eu/		E-mail: alf.elg@ri.se
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. RISE, Sweden	9. CIRCE, Spain	-
2. FFIL, Spain	10. RSE, Italy	
3. IMBiH, Bosnia and Herzegovina	11. TU Delft, Netherlands	
4. INRIM, Italy	12. UPM, Spain	
5. LNE, France	13. UPV, Spain	
6. TUBITAK, Türkiye	14. UTwente, Netherlands	
7. VSL, Netherlands		
8. VTT, Finland		
Associated Partners: 15. METAS, Switzerland		

Publishable Summary for 23IND02 COMET

Manufacturing of commutable calibrators and quality control materials for standardisation and post-market surveillance of IVD tests

Overview

Medical decisions often depend on accurate, informative and comparable biomarker measurement results from commercial in vitro diagnostic (IVD) tests. According to the in vitro diagnostic regulation (IVDR) EU/2017/746, the metrological traceability of values assigned to calibrators and/or control materials shall be assured through suitable reference measurement procedures (RMPs) and/or suitable Certified Reference Materials (CRMs) of a higher metrological order. Due to a lack of biological CRMs and RMPs (spanning from small molecules to protein to nucleic acids), IVD manufacturers are often unable to comply with regulation. This project will enable the IVD industry to meet the requirements of the IVDR EU/2017/746 regarding metrological traceability and performance verification of IVD tests. This will be achieved by establishing the necessary metrological infrastructure to provide cost-effective calibration services to IVD manufacturers to properly establish calibrated IVD tests and better monitor their performance. New certified reference materials and quality control materials will be produced for IVD tests which are in need for standardisation and post-market surveillance. By developing more efficient ways to conduct commutability studies, the project will identify common causes of poor commutability and improve the manufacturing process.

Need

According to the in vitro diagnostic regulation (IVDR) EU/2017/746, the metrological traceability of values assigned to calibrators and/or control materials shall be assured through suitable reference measurement procedures (RMPs) and/or suitable Certified Reference Materials (CRMs) of a higher metrological order. Due to a lack of biological CRMs and RMPs (spanning from small molecules to protein to nucleic acids), IVD manufacturers are often unable to comply with regulation.

The lack of higher order RMPs to assign target values to calibrators or quality control materials is due to i) the time needed to validate high accuracy methods with fit for purpose measurement uncertainties, ii) the cost to operate such labour-intensive methods and iii) the lack of primary calibrators of well-characterised purity. There is a need for more efficient purity assessment techniques to assign target values to primary calibrators, e.g., quantitative Nuclear Magnetic Resonance (qNMR) and for high-throughput RMPs, e.g., automated LC/MS/MS methods that can be used to provide cost-effective calibration services and value assign CRMs and quality control materials.

In addition to the lack of RMPs, the lack of secondary CRMs largely originates from the difficulty and cost to properly assess materials' commutability, which is a property describing their ability to properly mimic the behaviour of patient samples. The paramount importance of commutability has only been recognised recently and to date, however, causes for materials non-commutability remain largely unknown. As properly assessing commutability represents prohibitive costs for Reference materials (RM) producers, there is a need for more efficient and cost-effective ways of conducting commutability studies to identify suitable manufacturing processes.

To support manufacturers in post-market surveillance, there is a need to improve availability of External Quality Assessment (EQA) schemes using control materials of proven commutability and reference method target values.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: September 2024

Addressing these needs requires a coordinated metrological response involving all stakeholders: IVD manufacturers, EQA providers, RM producers, international organisations promoting standardisation.

Objectives

The overall aim of this project is to establish the necessary metrological infrastructure to provide calibration services to External Quality Assessment (EQA) providers and IVD manufacturers to evaluate and improve accuracy and harmonisation of medical test results. This will help the in vitro diagnostic industry meet the requirements of the In Vitro Diagnostic Medical Devices Regulation (IVDR) regarding calibration and performance verification of IVD tests.

The specific objectives are:

1. To improve the availability of fit for purpose calibrators and quality control materials that can be used by in vitro diagnostic (IVD) manufacturers and External Quality Assessment (EQA) providers for establishing and verifying metrological traceability of clinical measurements for various measurands including bilirubin, cyclosporine, Parathyroid Hormone (PTH), Human Cytomegalovirus (hCMV), estradiol, Point of Care Test (POCT) for glucose and a panel of clinically relevant biomarkers. To develop or optimise purity assessment techniques necessary to value assign primary calibrators which can be used to calibrate RMPs with fit for purpose uncertainties and limits of quantification ($U < 4\%$ and $LOQ < 1\text{ pg/mL}$ for estradiol, $U < 2.3\text{--}7.6\%$ for therapeutic drugs, $U < 5.2\%$ and $LOQ < 5\text{ pg/mL}$ for PTH). To assign SI traceable target values to existing or new secondary CRMs and EQA materials of well-characterised commutability.
2. To identify manufacturing processes for the production of calibration and quality control materials of high commutability levels. To evaluate and compare the commutability of various secondary CRMs and EQA materials so as to improve the understanding of key common causes of limiting materials commutability (WP3). To establish commutability acceptance criteria, measurement uncertainty will be considered at each level of the calibration hierarchy, as well as its impact on the quality of laboratory tests.
3. To develop more efficient and cost-effective ways of conducting commutability studies by e.g., mutualising the resources and capabilities of reference measurement service providers supporting a European Metrology Network infrastructure TraceLabMed (EMN TLM). To develop alternative strategies, such as abbreviated commutability studies, multiparameter commutability studies, the use of commutability panels, the use of high throughput RMPs and automated data analysis in order to make commutability assessment more straightforward.
4. To support post-market surveillance of IVD tests by working in close cooperation with EQA providers and IVD manufacturers. To assign reference method target values to existing EQA materials as well as to evaluate their commutability. Additionally, to organise at least one accuracy-based programme relying on commutable EQA materials with reference method target values. To combine EQA data obtained and to develop novel approaches for EQA data aggregation in order to evaluate harmonisation of measurement results on an international basis. (WP4)
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers, EMN TLM), standards developing organisations (e.g., ISO, CEN, CLSI), and end users (e.g., international organisations (e.g., IFCC, ICHCLR), assay manufacturers, material producers, EQA providers and medical associations).

Progress beyond the state of the art and results

Objective 1: Improved availability of commutable CRMs & EQA materials for high priority biomarkers

Commutable CRMs and EQA materials will be developed for high priority IVD tests for which there is an urgent need to properly establish results metrological traceability and/or better monitor results accuracy and harmonisation (neonatal bilirubin, cyclosporine, PTH, hCMV, estradiol, glucose). Primary calibrators of well characterised purity and identity will be developed for estradiol, cyclosporine and PTH. These will be used to calibrate automated and/or multiplexed RMPs delivering SI-traceable results with fit for purpose uncertainties ($U < 7.6\%$ for cyclosporine, $U < 5.2\%$ for PTH, and $U < 4\%$ for estradiol). The high throughput RMPs

previously developed will be used to value assign target values to secondary CRMs and EQA materials which commutability will be evaluated. New WHO International Standards for PTH and hCMV will be produced and their commutability will be evaluated.

Objective 2: Identification of manufacturing processes leading to high commutability levels

As the causes for a material's non-commutability remain largely unknown, various calibration and quality control materials will be sourced and/or prepared according to different manufacturing processes. Their commutability will be evaluated and compared with the objective to identify critical quality attributes of materials and key common causes limiting commutability. To define commutability acceptance criteria, measurement uncertainty will be considered at each level of the calibration hierarchy, as well as its impact on the quality of laboratory tests.

Objective 3: Development of more efficient and cost-effective ways of conducting commutability studies

As commutability evaluation is cumbersome, the project will develop more efficient and cost-effective ways of conducting commutability studies, including simplified commutability studies involving a reduced number of patient samples and/or a comparison with a material which commutability was successfully established in a previous study; multiparameter commutability studies in which commutability of a large number of CRMs and EQA materials will be evaluated simultaneously for a panel of measurands; use of commutability panels consisting of frozen pools which commutability was qualified beforehand; use high-throughput RMPs that are automated and/or multiplexed; mutualising the resources and capabilities of a coordinated network of reference laboratories that will share the work to jointly assign reference method target values to all study materials; development of a software for automated data analysis.

Objective 4: Novel approaches for EQA data aggregation

Results of accuracy and harmonisation will be evaluated for the prioritised biomarkers in order to support IVD manufacturers with post-market surveillance. This will be done using EQA materials of proven commutability and to which reference method target values will be retrospectively assigned by a coordinated network of calibration laboratories sharing the workload. For a wider panel of targets, a large-scale accuracy-based programme will be organised in which commutable, SI-traceable EQA materials will be distributed to a large number of medical laboratories from multiple European countries. Using EQA materials of proven commutability will make it possible to aggregate EQA data with confidence and to evaluate results comparability on an international basis.

The project will define needs, requirements and governance structure of a permanent organisation responsible to i) facilitate and coordinate the organisation of joint, multiparameter commutability studies, ii) promote and organise regular accuracy-based programmes and iii) support EQA data aggregation for improved post-market surveillance. This will have a lasting effect after the lifetime of the project.

Outcomes and impact

Key dissemination and communication activities

-

Outcomes for industrial and other user communities

IVD manufacturers will benefit from the improved availability of commutable CRMs and EQA materials to fulfil requirements of the IVDR EU/2017/746 regarding metrological traceability. IVD providers will be in a better position to demonstrate the analytical performance of their products and the correct implementation of metrological traceability. This will facilitate submissions for regulatory approvals and faster translation of products to market.

In addition to new reference standards (including candidate WHO International Standards for PTH and hCMV), the project will deliver high throughput RMPs to offer more cost-effective calibration services to the industry. This will help reducing the cost for manufacturers of validation studies in which large sets of samples are measured using RMPs.

IVD manufacturers will be offered the possibility to evaluate commutability of their own products and to perform measurements in their own facilities, which will promote uptake of the results. They will also be consulted to

select assays and materials to be included in commutability studies. As IVD providers will represent the key participant within the stakeholder's network and the advisory board, high uptake is foreseen.

Producers of RMs and quality control materials will also acquire better knowledge of the most appropriate sample formats and manufacturing processes. Production of pilot batches will be greatly reduced, which will generate cost savings and help material producers advertise quality of their products, e.g., to EQA providers.

To disseminate the project findings, the consortium will issue recommendations, guidelines, papers, newsletters, application notes, organise industry-oriented workshops and present the work at conferences.

Outcomes for the metrology and scientific communities

The development of new and advanced analytical techniques for purity evaluation and/or identity confirmation will accelerate the production of primary calibrators that can be used to i) calibrate RMPs used to value assign secondary CRMs, ii) produce secondary CRMs prepared by spiking of primary calibrator in a suitable matrix.

The project will develop new approaches to increase the throughput of RMPs. To reduce hand-on time, the project will advance automation and multiplexing, which will allow NMIs/DIs offering more cost-effective measurement services to IVD producers and EQA providers, resulting in growth of their use.

The project will greatly improve NMIs and DIs capabilities in commutability assessment of biological CRMs. The project will develop more efficient and cost-effective ways of running commutability studies. This will allow CRM producers to reduce the rate of non-conforming materials and reduce associated costs.

The project will raise awareness of the metrology community of the importance to take into consideration the need of industry and clinicians to have RMPs and CRMs with fit for purpose measurement uncertainties.

The project will define needs, requirements, and governance structure of a permanent organisation responsible to facilitate the organisation of joint commutability studies and coordinate the joint value assignment of reference method target values to share the work among the different calibration laboratories. This will make it possible to organise large-scale studies that are currently beyond the capabilities of single NMIs/DIs and bring the metrology community to a higher level of coordination and integration of capabilities of several institutes. This will promote the organisation of regular accuracy-based programmes and improve post-market surveillance.

To disseminate the project findings, the consortium will issue recommendations, guidelines, papers, newsletters, application notes, organise workshops at CCQM meetings and present the work at conferences.

Outcomes for relevant standards

The project will support assay validation and, thus, will enable IVD developers, clinical laboratories and other end-users to better comply with regulations and standards, e.g., IVDR, ISO 15189, 17025 and 17511. The project will support stakeholder-driven standardisation initiatives through the provision of higher order CRMs compliant with ISO 15194, RMPs compliant with ISO 15193 and measurement services compliant with ISO 15195. Outputs of the project will be incorporated into relevant standards, recommendations, and guidelines in development. This will be achieved taking into consideration participants' involvement in 36 standard committees, working groups, task forces and standardisation initiatives, including ISO, CLSI, IFCC, JCTLM and CCQM.

Longer-term economic, social and environmental impacts

For the IVD industry, given the growing market size in the overall Med Tech sector, the lack of metrological concepts to de-risk IVD development, the support of translation and application of diagnostic tests represents a significant bottleneck. The outputs of this project will aid in reducing the associated risks by improving the references required to support the development of measurement kits for accurate clinical measurements.

Medical laboratories will benefit from using more reliable IVD tests that have been correctly validated by manufacturers. They will also benefit from more informative EQA schemes to evaluate assay performance and ensure that results meet the necessary quality and accreditation requirements (ISO 15189, ISO 17025). This will increase confidence and reliability of results interpretation and medical decisions made by biologists.

Patients will benefit from more reliable diagnostics and more appropriate treatments.

Clinical researchers, drug developers and epidemiologists will also benefit from harmonised data that can be compared and combined regardless of what assay was used for generating them. This will make it possible to

aggregate large datasets and employ AI / big data approaches more reliably, e.g., in the context of clinical trials and epidemiological studies. This will result in a better understanding of pathologies and facilitate the validation of new therapies.

Healthcare systems will benefit from improvements in post-market surveillance of IVD tests to better identify diagnostic tests not meeting the required quality and that should not benefit from reimbursement. This will contribute to reducing unreliable tests and saving money. For example, it was estimated that for calcium (Ca) testing, a 0.1 mg/dL bias can cost \$8 - \$31 for additional, but unnecessary, patient follow up testing, which translates into \$60 - \$199 million/year. Reduced economic burden will also arise from a better management of patients.

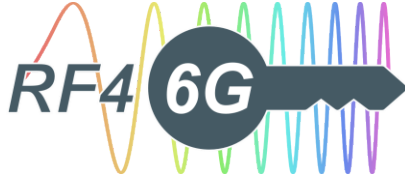
Through communications to the general public (e.g., patient-oriented newsletters), the project will help better appreciating the importance of medical test reliability and of metrology.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2024, 36 months
Coordinator: Vincent DeLatour, LNE Tel: +33 615 206 957 E-mail: vincent.delatour@lne.fr		
Project website address: -		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. LNE, France	6. CHUL, Belgium	14. Archem, Türkiye
2. INRIM, Italy	7. CHUM, France	15. INVENT, Germany
3. NIB, Slovenia	8. HDS, Norway	16. Roche, Germany
4. PTB, Germany	9. INSTAND, Germany	
5. TUBITAK, Türkiye	10. Sciensano, Belgium	
	11. SPMD RfB, Germany	
	12. UGent, Belgium	
	13. UMK, Poland	
Associated Partners:		
17. EQALM, Switzerland		
18. LGC, United Kingdom		
19. MHRA, United Kingdom		



Publishable Summary for 23IND03 RF 4 6G RF key quantities for 6G development

Overview

The swift advancement of the upcoming 6G wireless technology anticipates deployment in the early part of the next decade, featuring remarkable specifications geared towards powering digital and highly connected applications. This project aims to extend the metrological support for RF key quantities in line-based systems with connectorised interfaces to meet the challenges being set by the 6G specifications. It will provide foundational support to industries involved in ongoing R&D efforts, fostering the rapid evolution of 6G and strengthening the position of European industries in this fast-growing field.

Need

This project addresses the critical need for advanced metrological capabilities in the realm of RF (Radio Frequency) measurements, primarily to support the rapid development of 6G wireless communication technologies. At a high level, the societal need is to propel Europe into a leadership position within the global telecommunications industry by fostering innovation and ensuring the reliability of emerging 6G technologies. The success of these technologies is paramount for various industries, including autonomous mobility, the Internet of Things (IoT), artificial intelligence, and more.

End users, encompassing industries, manufacturers, and researchers, require precise and traceable RF measurements for multiple purposes. These needs range from the development and characterisation of cutting-edge components and devices for 6G networks to ensuring the seamless integration of RF technologies in various applications. Without advanced metrological capabilities, end users face challenges related to the accurate measurement of RF power, phase, and waveform parameters, as well as limitations in traceability and calibration.

6G development efforts are leading to operating frequencies above 200 GHz to enable the anticipated high data rates. Specific measurement needs include the development of primary standards for RF power measurements up to 220 GHz, the expansion of coaxial connector frequency limits up to at least 220 GHz, the establishment of traceable calibration procedures for electrical waveform parameters above 110 GHz, and the creation of new ways to measure linearity and, based on that, novel attenuation standards. These capabilities are crucial for ensuring the reliability and performance of future 6G systems, reducing development costs, and enabling European industries to compete effectively on a global scale.

By addressing these measurement challenges, the project aims to enable and accelerate the development of 6G technologies, enhance Europe's industrial competitiveness, and support various sectors in harnessing the transformational potential of the next generation of wireless communication.

Objectives

The overall goal of this project is to extend metrology for RF key quantities in line-based connectorised systems in frequency and in time domain for optimal support of 6G wireless developments. The specific objectives of the project are:

1. To develop waveguide based primary standards (microcalorimeter) for RF power measurements up to 220 GHz. To develop a microcalorimeter capable transfer standard (for the traceability transfer to

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PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership Co-funded by the European Union

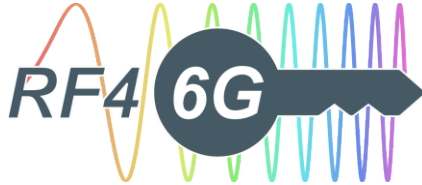
Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: May 2024



secondary standards) up to 220 GHz. To evaluate novel concepts for a transfer standard, which could operate to even higher frequencies (e.g., 330 GHz).

2. To extend the frequency range of broadband coaxial connectors by pushing up the standardised frequency limits of existing coaxial line systems and establish traceability for new coaxial sub-mm connectors up to 220 GHz. To develop phase standards based on novel concepts, as e.g., a calculable diode, for non-linear/large signal S parameter measurements to at least 67 GHz. To develop and validate novel linearity characterisation methods for different vector network analyser (VNA) setups up to 220 GHz. To develop a novel VNA based primary attenuation standard up to 220 GHz.

3. To establish traceable calibration procedures for electrical waveform parameters up to a 3 dB bandwidth of at least 145 GHz. To demonstrate the characterisation of a high-speed photodiode module suitable for datacom and telecom applications.

4. To engage with industry to ensure that the specifications of measurement and test systems required by 6G developers can be met by device and component manufacturers. To directly involve industry in the project as component and system suppliers to allow for maximum uptake.

5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (ISO/IEC/ETSI), and end users (e.g. telecommunication network infrastructure, manufacturers of components and system suppliers). To update EURAMET calibration guides.

Progress beyond the state of the art and results

Objective 1

RF Power: Waveguide-based Primary Standards

Microcalorimeters are primary RF power standards operated at a few NMIs all over the world. The current upper frequency limit of these waveguide-based standards is 170 GHz. This was established in the project EMPIR JRP 18SIB09-TEMPT by building a set-up for the D band. This project will build microcalorimeters for the next waveguide band, which are operable up to 220 GHz.

RF Power: Transfer standards

The upper frequency limit for existing power sensor transfer standards (microcalorimeter capable) is limited to prototypes, which operate up to 170 GHz. They were developed in EMPIR JRP 18SIB09-TEMPT and are expected to become commercially available soon. This project will develop waveguide transfer standards up to 220 GHz in direct collaboration with industry. A conceptual study for transfer standards to even higher frequencies (up to 330 GHz) will be undertaken as well as investigations to improve measurement uncertainties at low frequencies (<1 GHz) by applying quantum standards (JAWS).

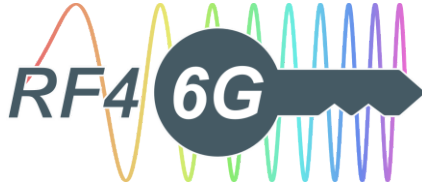
Objective 2

S-parameter: Extending Frequency Range of Coaxial Measurements

The upper frequency limit of coaxial connectors is currently limited to 110 GHz (1 mm connector, this was established in the project EMRP JRP SIB62-HFCircuits) and the existing coaxial line systems are not specified to operate at their theoretical upper limit specified by the size of the transmission line. This project will extend frequency limits of coaxial connectors in a collaborative effort between industry (providing mode-free components) and NMIs (extending traceability of existing systems). This project will also establish traceability for new coaxial sub-mm connectors and push the upper frequency limit beyond 110 GHz, for the 0.8 mm connector to at least 150 GHz and for the 0.5 mm connector to at least 220 GHz.

S-parameter: linearity/attenuation

Existing attenuation standards are high maintenance and costly in operation. By nature, they are low frequency devices and for higher frequencies they employ frequency-mixing. Matching and stability conditions become a concern with increasing frequencies. This project will extend innovative VNA based methods to determine the



linearity for various VNA systems reaching up to 220 GHz and develop novel concepts for VNA based primary attenuation standards.

S-parameter: non-linear/large signal measurements

Today's standards for inter-frequency phase relation are electro-optical wave form standards. They are difficult and costly to operate. Traceability is elaborate and currently limited to two NMIs worldwide. This project will investigate a novel primary standard in the frequency domain. It is based on a calculable diode, which will be provided by the industrial participants and characterised by the NMIs and academic participants. The concept has a potential for lower costs, less maintenance, easier reproducibility, and wider distribution.

Objective 3

Electrical Waveform Parameters

Currently, the transfer characteristics and intrinsic time responses of high-speed electronic devices can be traceably calibrated up to a frequency limit of 110 GHz. Using an electro-optically operated voltage pulse standard, the frequency restriction results from the 1 mm coaxial connection of the DUT. The project will extend this capability to 145 GHz utilising 0.8 mm coaxial connector devices, characterised in the S-parameter objective.

Objective 4

Engagement with industry

By combining direct industry collaboration with innovative outreach methods, this project is designed to engage with and influence the industry beyond the current standards. The project will actively involve many diverse industry participants within the consortium, integrating their expertise in planning, component supply, and project evaluation. Through workshops, publications in trade journals, and the enhancement of a calibration guide, the project will extend its influence. These efforts go beyond conventional practices, ensuring widespread impact on industry practices and standards.

Outcomes and impact

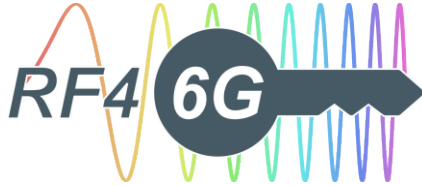
Outcomes for industrial and other user communities

The project is expected to yield significant outcomes for industrial and user communities through the development of advanced measurement capabilities. Primary among these outcomes is the development of waveguide-based primary standards for RF power measurements up to 220 GHz. This advancement will provide industries reliant on high-frequency RF technologies, such as telecommunications, wireless communication, and radar systems, with highly accurate and traceable measurement standards. Manufacturers of RF components and test equipment will particularly benefit from these improved measurement capabilities, as they will enhance the quality and reliability of their products.

Moreover, the extension of the frequency range for broadband coaxial connectors to 220 GHz and the establishment of traceability for new coaxial sub-mm connectors will directly impact industries that utilise high frequency connectors in their applications. This includes industries such as aerospace, defence, and telecommunications, which will benefit from improved connector standards and traceability, resulting in enhanced product performance and interoperability.

The project will also have positive outcomes for end users in the field of datacom and telecom applications. The high-speed photodiode module characterisation and the establishment of traceable calibration procedures for electrical waveform parameters will lead to the development of more reliable and efficient datacom and telecom devices, benefiting consumers and businesses relying on high-speed data transmission.

The impact on the industry will be particularly effective because key players of the above-mentioned industries will actively contribute to the project by developing components and providing resources. The uptake will be direct and immediate.



Outcomes for the metrology and scientific communities

RF power and S-parameters in the frequency domain and waveform parameters in the time domain are key parameters in RF and microwave metrology. The project's results will significantly advance the traceable measurement capabilities into new frequency domains. The extended measurement capabilities will gain international recognition and acceptance through new and updated Calibration and Measurement Capabilities (CMCs), which will be submitted to the KCDB (the BIPM key comparison database). European NMIs will be able to provide traceability and measurement reliability in globally uncharted territory, thus putting the significance of European RF and microwave metrology at the forefront.

Furthermore, the project is seeking to innovate metrology by leaving beaten paths and exploring new ways. This refers to the new linearity/attenuation concept and the calculable diode as a novel phase standard, which will be explored in the project. The entirely VNA based linearity/attenuation approach has the potential to overcome limitations of existing established standards and will be applicable in frequency domains relevant to 6G developments. The calculable diode as a phase standard is a synonym for collaborative scientific excellence at its best. It combines industrial advanced manufacturing, NMI measurement excellence and academic scientific capability.

Outcomes for relevant standards

The project's outcomes will impact standards development organisations by providing valuable inputs for the revision and creation of documentary standards. The extension of the frequency range for broadband coaxial connectors and the establishment of traceability for new sub-mm connectors will trigger a revision of the IEEE P287 and the IEC 61169 standards (related to IEC-TC46) on coaxial connectors. The work on the waveform parameters will serve as input to IEC 62754 (related to IEC TC85 WG 22 and DKD/DKE D 964), the computation of waveform parameter uncertainties. The work on linearity and attenuation will provide input to an update of IEEE P1765 on modulated signals.

The EURAMET calibration guideline cg-12 on VNA measurements is not an official standard, but it is a widely accepted document, which is used by the measurement supply chain for accurate and reliable VNA measurements. The project's results on the coaxial connectors and linearity/attenuation will provide input for an update of EURAMET cg-12.

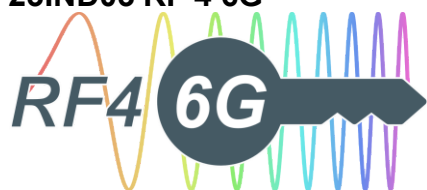
Longer-term economic, social, and environmental impacts

Economically, the improved measurement capabilities and traceability will result in more reliable and efficient RF and microwave devices, leading to economic growth in industries dependent on high-frequency technologies. This includes telecommunications, aerospace, defence, and datacom, where enhanced product quality and performance will drive market competitiveness. The project will contribute to the 6G roadmaps, for example those laid out by the Next G Alliance or 6G IA, in a fundamental way. The applications built on 6G will create business opportunities and new jobs.

Socially, the project's outcomes will contribute to the development of innovative technologies that underpin modern communication systems, benefiting society by enabling faster and more reliable wireless communication, radar systems for industry sensing and disaster management, and data transmission for telemedicine. These advancements will enhance the quality of life and safety for individuals and communities. The 6G technology aims at data rates up to 1 Tbps. This will speed up the digital transformation of the society and enable completely new applications and services. 6G aims at ultra-low latency down to microseconds and high reliability for mission and liability critical applications, e.g., autonomous driving. Trust in measurements through traceability becomes increasingly mandatory for applications with strong safety and real-time aspects. This project will contribute to it in a fundamental way and help that new safety critical applications and services will obtain acceptance.

From an environmental perspective, the project's outcomes will support the development of more energy efficient RF and microwave systems, reducing power consumption and contributing to a greener future. Additionally, the increased accuracy and reliability of measurement standards will lead to more efficient testing and calibration processes, minimising waste and resource consumption.

In summary, the project's impact will be felt across multiple sectors, from industry and metrology to scientific research and standards development. Its outcomes will foster innovation, economic growth, and improved



quality of life, reinforcing Europe's leadership in high-frequency metrology and its contributions to global technological advancements.

List of publications

No publications yet

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration: 1 st May 2024		36 Months
Coordinator: Frauke Gellersen, PTB		Tel: +49 531 592 2222
Project website address: https://www.ptb.de/epm2023/rf46g/home		E-mail: frauke.gellersen@ptb.de
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CMI, Czechia	6. FAU, Germany	7. Anritsu AU, Austria
2. INRIM, Italy		8. Antevorta, Netherlands
3. LNE, France		9. Keysight BE, Belgium
4. TUBITAK, Türkiye		10. R&S, Germany
5. VSL, Netherlands		11. Spinner, Germany
Associated Partners:		
12. BHAM, United Kingdom		
13. ETHZ, Switzerland		
14. Flann, United Kingdom		
15. METAS, Switzerland		
16. NPL, United Kingdom		
17. VDI, United States		

Publishable Summary for 23IND04 MetSuperCap

Metrology for static and dynamic characterisation of supercapacitors

Overview

Supercapacitors (SCs), an environmentally friendly technology, are being used as energy-storage devices across an increasing number of fields, including as a replacement for batteries in higher-power density applications. This electrochemical energy storage device has an operating principle and charge storage mechanism which is more closely associated with those of rechargeable batteries than electrostatic capacitors. However, as the behaviour of SCs differs from both, and in order to support the growing use of SCs, accurate characterisation is required for SCs and SCs banks, both in the laboratory and under operating conditions. In addition to this, validated software is needed to identify the equivalent electrical model of SCs for dynamic applications. Quick, traceable, and effective measurement techniques are also required to evaluate the State of Charge (SoC) and State of Health (SoH) of SCs and to promote the uptake of SCs in industrial and energy applications.

Need

The EU's Batteries Directive 2006/66/EC aims at improving the protection, preservation, and quality of the environment by, for example, imposing maximum quantities for certain types of metals and chemicals contained in batteries. SCs, an environmentally friendly technology, strongly reduce the presence of certain chemicals and metals, which is unavoidable in many types of batteries. In addition, the life cycle of SCs is very long (a hundred times longer than batteries), their charging and discharging limits are not critical, unlike for batteries, and they pose zero thermal runaway risk over a wide temperature range. These devices can be used, amongst others, in industrial and energy applications but their uptake and future commercialisation is currently hampered due to technical problems and a lack of established electrical parameter models, consistency in testing, and industrial standards.

SCs metrics are only partially defined by manufacturer guidelines and standards and these furthermore lack the appropriate accuracy analysis. Therefore, guidelines on the methods for accurate characterisation of SCs and banks are needed. To implement SCs and SC banks into applications, reliable tools for the accurate determination of a multiparametric equivalent circuit model (ECM) are needed. A clear measurement and identification tool is not within the knowhow of many companies. A reliable and recognised tool would allow designers and manufacturers to easily implement SCs into a wide range of applications. Applications require frequent monitoring of the SoH and SoC of the supercapacitive components to provide correct feedback to the users and to ensure a sufficient maintenance schedule is in place. Therefore, developing rapid and reliable methods of measurement and diagnosis is of great interest for many applications. In specific applications, for example, the coexistence of batteries and SCs may lead to complex charging management systems. New models and methods developed for SCs have to be verified in the presence of distorted waveforms (low power quality) and the limits of their validity 'in operation' must be defined. Finally, it should be noted that to date almost all the studies, standards and guidelines mainly concern Electric Double Layer Capacitors (EDLCs) while new guidelines for the characterisation of SCs also need to take into account hybrid SCs and pseudo-SCs.

Objectives

The overall objective of the project is to establish a traceable, consistent and sound measurement and characterisation framework for both SCs and SC banks. This includes the development of rapid techniques for

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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EURAMET

Issued: June 2024

the determination of SoC/SoH of SCs, for the determination and assessment of ECM parameters, the verification of the proposed techniques in real conditions and the processing of inputs for standards developing organisations.

The specific objectives of the project are:

1. To develop metrologically traceable methods, including the assessment of uncertainty, for characterising the capacitance, resistance, specific power and energy for SCs of different sizes (from 1 farad to 3000 farads, for discharge currents up to 500 A and voltages up to 60 V) and at least two different types and brands. The developed methods should be suitable for the characterisation of SCs banks with maximum instantaneous discharge power up to 25 kW (e.g., 420 A at 60 V).
2. To develop software/models for identifying relevant parameters for the static and dynamic characterisation of SC and SC bank models. The target error of the developed software/models will be lower than 5 % (for voltages greater than 200 mV). In addition, to define optimised voltage/current waveforms, based on representative SC charging and discharging cycles, for characterising SCs and for validating models by measurement.
3. To develop rapid techniques, including the assessment of uncertainty, for accurately measuring the SoC and SoH of SCs. Additionally, to test and verify the developed techniques on at least two different types of SCs.
4. To design and produce two test benches fitted with a measurement system and a measurement procedure to evaluate the actual behaviour of SCs under operating conditions, including battery/emulator-SCs hybrid systems. The test benches will also be used for the validation of the outputs of Objectives 1 3 and for the evaluation of at least two applications of SCs in energy systems, (e.g., photovoltaics (PV), uninterrupted power supplies (UPS), electric vehicles (EVs)).
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (those associated with the EU's Batteries Directive 2006/66/EC), and end users (e.g., EMN for Smart Electricity Grids, the aerospace, automotive and energy sectors).

Progress beyond the state of the art and results

SCs and banks of SCs require time-demanding testing, and research laboratories often provide tests which are limited in terms of physical conditions and the SCs sample analysed. This project will go beyond the state of the art, by providing a large database of electrical parameters of SCs and SC banks of various and sizes and brands made available to the public via Open Access (OA).

Measurement of the parameters of SCs and SC banks

The approach suggested by the standards is sometimes relaxed in terms of accuracy of the SC parameters determination. For instance, the standard EN IEC 62391-1:2022 details that current and voltage measurement accuracy should be about ± 1 % or less. Relaxed accuracy limits for the instrumentation result in equally large uncertainties on the SC parameters. The project will go beyond the state of the art by developing a guide that provides a clear relationship between the instrumentation, the measurement method, and the expected uncertainty on the SC parameters.

Equivalent Circuit Models of Super Capacitors

Multiple approaches for modelling SCs have been presented in the literature. These ECM models are quite promising due to their strong application value, as they allow the equivalent circuit of the SC to be directly implemented into complex control systems which can include charge control and the load. This project will go beyond the state of the art by improving the target error of ECM models and software to 5 % and extending the use to a wide variety of SCs sizes and types, testing the validity of such models also with real waveforms.

State of Health and State of Charge determination

The determination of SoC and SoH allows systems to increase reliability, predictive maintenance and real time condition monitoring. Rapid methods are not common but are of great applicative interest and the determination of the SoC/SoH requires the use of complex techniques or the use of complex algorithms combined with the device's ECM. This project will progress the state of the art by exploring the possibility of

using rapid (e.g. impulsive) measurement techniques and other approaches linked to ECM parameters, in order to obtain a reliable SoC/SoH assessment.

Real applications with hybrid “SC plus battery” systems

The use of SCs in conjunction with batteries provides undoubted advantages in terms of absorption and return of power peaks which, managed by SCs, improve efficiency, and extend the life of the batteries. Applications for such hybrid devices, e.g. electric vehicles, require the development of hybrid charge control systems, which are beyond the state of the art and go beyond a common battery management system. Furthermore, the operation of SCs in real conditions requires further studies and validations. This project will provide a clear picture of how laboratory determinations can be applied in real conditions.

Outcomes and impact

Outcomes for industrial and other user communities

The good practice guide for evaluating the uncertainty of electrical parameters (e.g. capacitance, resistance, specific power and energy) in SC testing and characterisation, covering a wide range of SC sizes (1 – 3000 F) developed within the project will enable SCs users, designers and SC manufacturers to simplify the characterisation of SCs and SC banks. A widely-recognised standard procedure associated with a metrological infrastructure providing the traceability for such assessment will provide higher trust to both the customer and the manufacturer.

The methodologies and procedures for the accurate determination of the characteristics of the SCs will improve the reliability and accuracy of these parameters which are crucial for designers and users, especially for more demanding applications, such as space, e-mobility and energy applications. The validation of the methodologies for the use of SCs in real conditions, verified for different types and sizes of SCs, will allow manufacturers of systems using SCs (e.g., for renewables, automotive applications, e-mobility in general) to design more robust technical solutions and better plan predictive maintenance.

An ECM validated and verified on a large sample of SCs, for real-time applications, will provide a useful reference for SC manufacturers and provide an additional design parameter. Instrument and SC manufacturers will use the advanced hardware for the characterisation of SCs in pilot lines to improve the accuracy and reliability in parameter assessment, providing better specifications for their products, with consequent benefits also for users and designers.

The rapid techniques for determining the SoC/SoH of SCs can be used by manufacturers of electronic systems that use SCs as power supply units, increasing the reliability of the systems and allowing the successful implementation of predictive maintenance techniques. These techniques are also important for manufacturers of aerospace and e-mobility storage systems. The availability of two large databases, one regarding the characterisation and characteristics of SCs and a second developed regarding the SoC/SoH of SCs could constitute a benchmarking for manufacturers for the development of new products.

Outcomes for the metrology and scientific communities

The project will provide the scientific community with traceable measurements for the characterisation of SCs and banks of SCs. The validity of the proposed measurement techniques will also be verified in operation (i.e., with ripple and harmonics) and consider new types of hybrid SCs. The guidelines for these measurements can be used by other metrologists to meet the measurement needs of the national industries producing and using SCs. The project will provide scientific and technical knowledge on such precision measurement systems to electrical metrologists, researchers in the field of storage and its applications in e-mobility, energy and power electronics from related academic fields for further development. The consortium will provide an overview of the measurement accuracy obtainable with the most well-known DC measurement techniques and Electrochemical Impedance Spectroscopy (EIS) techniques, that currently does not exist either for manufacturers or in scientific publications, except for individual analyses under controlled conditions and generally on a few types or sizes of SCs.

NMIs will deliver a report containing the CMCs concerning the characterisation of SCs, compliant with those published in the KCDB website, which will be ready for use in NMIs depending on market demand in the various countries. These CMCs will be of high relevance to the metrology community, as at the moment no NMIs deal with high capacitance measurements, especially in the 10 F – 3000 F range, which is the one that is receiving great interest in SC applications.

The two large open access databases that group together a significant amount of relevant data on different types of SCs, will enable academic communities (both metrological and non-metrological with limited or no capabilities to perform measurements and characterisations on SCs) to undertake further research activities including analysis of data and information about SCs' variability versus charging conditions, versus charging patterns, versus SoC/SoH and related aging.

The development of rapid techniques for the definition of SoC/SoH also requires the development of both analysis and measurement techniques. These developments will benefit both the metrology and scientific community since they can improve and speed up the assessment of these parameters.

Outcomes for relevant standards

The project will support the EU's Batteries Directive 2006/66/EC which aims at improving the protection, preservation, and quality of the environment by, for example, imposing maximum quantities for certain types of metals and chemicals contained in batteries. The project, by promoting the use of SCs combined with batteries, allows, for the same power supplied, to reduce the part borne by the battery and also significantly reduces the amount of energy borne by the battery. This indirectly leads to a reduction in the metal-pollutants embedded in the battery, reducing the related risk associated with disposal.

In addition, the consortium will promote the results of the project within the standardisation community and will provide input into the standardisation process (such as IEC TC40 and IEC TC113). The participants who are in contact or are members of corresponding technical committees will inform them about the results of this project and will endeavour to ensure they are incorporated in any updates to the standards or guidelines.

Longer-term economic, social and environmental impacts

The contribution to SoC/SoH assessment provided by the project has a significant impact on predictive maintenance techniques, which is a key factor boosting the growth of this technology, whose market is already expected to double in the next 5 years. Promoting the diffusion of SCs in electrical systems by design, and their adoption, also means meeting the needs of the European Strategic Energy Technology (SET) Plan, which provides a roadmap to enable the transition towards a climate neutral energy system through the development of low-carbon technologies. SCs, differently from the batteries, do not require the use of rare or polluting materials and, on the contrary, can also implement organic materials, constituting an environmentally friendly component. To promote the diffusion of SCs also responds to the social demand for high-capacity portable power supply that is becoming more and more crucial.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		June 2024, 36 months
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Project website: tbd		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. INRIM, Italy	6. CRF, Italy	n/a
2. CMI, Czechia	7. Keysight AT, Austria	
3. LNE, France	8. Novac, Italy	
4. RISE, Sweden	9. Pleione, Germany	
5. VSL, Netherlands	10. POLITO, Italy	
	11. UNIGE, Italy	
	12. UTwente, Netherlands	



Publishable Summary for 23IND05 H2FlowTrace

Flow measurement traceability for hydrogen in gas networks

Overview

To avoid the worst impacts of climate change, greenhouse gas emissions need to be dramatically reduced. This will only be possible by reducing the EU's reliance on fossil fuels. Hydrogen offers a sustainable alternative, which can be distributed through gas networks, with the ability to fulfil societal, economic, ecological and technological objectives. Hydrogen can be stored underground, or in the existing natural gas network, which allows it to meet fluctuating energy demands in a way that is not practical for renewable energy sources such as solar and wind. Although large-scale decarbonised hydrogen projects are expanding across Europe, there is no large-scale verified metrological infrastructure to perform traceable pure hydrogen flow calibrations for gas networks. This project will address this by contributing to the development of the required metrological infrastructure, which has the potential to reinforce Europe's leading position in the hydrogen economy.

Need

The EU is committed to making Europe the first climate neutral continent by 2050. Achieving this highly ambitious goal requires the complete transformation of the European energy system, which accounts for more than 75 % of the EU's greenhouse gas emissions [1]. Even in the medium-term, hydrogen will help meet the EU's 2030 climate and energy targets with the installation of at least 40 GW of electrolyzers which will produce 10 million tonnes of green hydrogen annually, and another 10 million tonnes will be imported. The EU's strategies on hydrogen and energy system integration (Next Generation EU recovery package [2], the European Green Deal [3], the EU Hydrogen Strategy [4]) will pave the way towards meeting this objective, but they also create significant technical, operational and safety challenges (e.g., traceable flow measurement, material compatibility, leakage, stricter Atmospheres Explosibles (ATEX) Directive 2014/34/EU requirements).

To achieve these targets the development of a hydrogen infrastructure needs to be rapidly accelerated. Pipelines are considered the most efficient solution to deliver high volumes of hydrogen, especially over long distances. In the last update, the European Hydrogen Backbone initiative [5] (31 European network operators with infrastructure in 28 European countries) stated a geographically extended vision for a dedicated hydrogen infrastructure stretching across these countries. By 2040, the proposed backbone could have a total length of almost 53,000 kilometres, consisting of approximately 60 % repurposed infrastructure and 40 % of new hydrogen pipelines. However, the lack of dedicated large-scale traceability, i.e., at flow rates and pressures applicable to the transmission and distribution gas networks, for the custody transfer of hydrogen, or hydrogen enriched natural gas (HENG) applications, is a major-well-known issue for fair trade in Europe. European network operators are asking National Metrology Institutes for hydrogen calibration services (addressed by Objectives 1, 2, 3), for their large-scale applications, in order to determine if traditional services could be used with calibration fluid transferability methods (Objective 4), or if actual hydrogen gas calibrations are needed.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: September 2024r

Objectives

The overall objective of the project is to establish gas flow traceability for hydrogen in gas networks. The specific objectives are:

1. To establish a robust metrological infrastructure for flow rates up to 1300 m³/h at 0.1 MPa or 45 m³/h at 3.3 MPa(g) with a primary focus on pure hydrogen, but also enabling traceability for hydrogen/natural gas blends in small industrial meters, with a measurement uncertainty of 0.20 % or less.
2. To establish a robust metrological infrastructure for flow rates of 200 m³/h to 10 000 m³/h, and pressures of 0.3 MPa(g) to 6.2 MPa(g) for pure hydrogen and hydrogen/natural gas blends in large industrial meters, with a measurement uncertainty of 0.30 % or less.
3. To design and test traceability transfer skids for pure hydrogen and hydrogen/natural gas blends. In addition, to carry out intercomparisons to determine the equivalence of independent traceability chains based on primary standards, secondary standards using a bootstrapping/upscaling approach, and secondary standards calibrated with alternative fluids to hydrogen.
4. To perform (i) primary calibrations of domestic gas meters (ultrasonic, diaphragm, thermal mass flow) with air and/or methane and with pure hydrogen up to 30 m³/h at atmospheric pressure and (ii) primary and secondary calibrations of industrial gas meters (ultrasonic, rotary, turbine) with air and/or natural gas and hydrogen/natural gas blends at flow rates of up to 1000 m³/h and pressures of up to 6.2 MPa(g). Based on these results as well as existing data, to deliver statistically meaningful datasets for air, natural gas, or other alternative fluid calibration for the transferability to hydrogen gas flow conditions for domestic and industrial flow meters.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited calibration and testing laboratories, European Metrology Network for Energy Gases), standards developing organisations (ISO TC 30, OIML TC 8/SC 7, CEN/TC 237) and end users (energy gas transmission, distribution operators, FARECOGAZ, ENTSG, Hydrogen Europe).

Progress beyond the state of the art and results

To establish a robust metrological infrastructure for flow rates up to 1300 m³/h at 0.1 MPa or 45 m³/h at 3.3 MPa(g) with a primary focus on pure hydrogen, but also enabling traceability for hydrogen/natural gas blends in small industrial meters, with a measurement uncertainty of 0.20 % or less. (objective 1)

This project will ensure the traceability for pure hydrogen / HENG for small industrial meters by delivering a small-scale transfer skid using sonic critical flow venturi nozzles (CFVN) (for flow rates up to 720 kg/h – 7800 m³/h at 0.1 MPa(g) or 270 m³/h at 3.3 MPa(g)) with a bootstrapping approach that uses the primary standards developed within the EMPIR JRP 20IND11 MetHyInfra. The targeted measurement uncertainty is 0.20 % or less.

To establish a robust metrological infrastructure for flow rates of 200 m³/h to 10 000 m³/h, and pressures of 0.3 MPa(g) to 6.2 MPa(g) for pure hydrogen and hydrogen/natural gas blends in large industrial meters, with a measurement uncertainty of 0.30 % or less. (objective 2)

This project will gather and collate information from previous projects on the traceability of flow metering (EMPIR JRPs 18NRM06 NEWGASMET [6], 20IND10 DECARB [7] and 20IND11 MetHyInfra [8], and Metrology Partnership JRP 21GRD05 MET4H2 [9]) in order to build on the knowledge acquired and to provide the missing large-scale traceability for hydrogen and HENG applications. This will ensure traceability for large industrial meters by design and testing a large-scale transfer skid, using master meters, which will go beyond the state of the art by offering traceability and a path to accreditation for pure hydrogen and HENG (for flow rates up to 1000 m³/h at 6.2 MPa(g)) for large scale flow metering. The targeted measurement uncertainty is 0.30 % or less.

To design and test traceability transfer skids for pure hydrogen and hydrogen/natural gas blends. In addition, to carry out intercomparisons to determine the equivalence of independent traceability chains based on primary

standards, secondary standards using a bootstrapping/upscaling approach, and secondary standards calibrated with alternative fluids to hydrogen. (objective 3)

The largest European hydrogen or HENG testing facilities will derive their traceability directly via the small-scale and large-scale transfer skids developed during this project. These infrastructures will be able to claim realistic and verified uncertainties during a laboratory comparison with a validated transfer standard (the transfer skid), which will be fully traceable to pure hydrogen gas flow. Some existing calibration facilities currently base their traceability chains on alternative fluids. During the facility intercomparison, the validity of this alternative fluid approach will be evaluated, by direct comparison with the hydrogen primary standards and bootstrapping approaches. The SSTs and LSTs, designed and tested in this project, will be used to deliver hydrogen and HENG traceability for gas networks after the project's end date.

To perform (i) primary calibrations of domestic gas meters (ultrasonic, diaphragm, thermal mass flow) with air and/or methane and with pure hydrogen up to 30 m³/h at atmospheric pressure and (ii) primary and secondary calibrations of industrial gas meters (ultrasonic, rotary, turbine) with air and/or natural gas and hydrogen/natural gas blends at flow rates of up to 1000 m³/h and pressures of up to 6.2 MPa(g). Based on these results as well as existing data, to deliver statistically meaningful datasets for air, natural gas, or other alternative fluid calibration for the transferability to hydrogen gas flow conditions for domestic and industrial flow meters. (objective 4)

Calibrations will be performed for at least 25 domestic and 15 industrial gas flow meters, using hydrogen, HENG and alternative fluids. This will be a larger sample than has been tested in any other project to date. The evaluation of mathematical models for the transferability of alternative fluid calibrations for each flow metering technology will be a meaningful outcome for the National Metrology Institutes and for the end users (gas network operators, energy companies, gas providers). It will be the first time that a large dataset for calibrations with air, natural gas, nitrogen, helium, hydrogen and HENG (from this project and previous EURAMET and national projects) will be analysed to determine the robustness of using alternative gases instead of the real application gas. This dataset, which is sought after by the industry, will be extremely valuable and it will be made available from the project through its open science practices.

Outcomes and impact

Outcomes for industrial and other user communities

This project will create impact on the Transmission System Operators' (TSOs), Storage System Operators' (SSOs) and Distribution System Operators' (DSOs) hydrogen blending strategies. Many European natural gas operators already released roadmaps targeting 2030 or 2050 for decarbonising the gas infrastructure. The retrofitting and repurposing of existing gas grids will provide an opportunity for a more cost-effective energy transition in combination with a (relatively limited) newly built infrastructure dedicated to hydrogen. Using the existing natural gas networks for hydrogen transport could require the repurposing or substitution of already installed measuring devices. With this in mind, the outcomes of this project will support accurate transmission and distribution, in a safe and cost-effective manner, removing the most-critical barriers for the adoption of hydrogen as an energy gas.

National Metrology Institutes are currently receiving more and more requests from the industry for traceable hydrogen calibration services for their metrological flow meters. However, as large-scale hydrogen metrological infrastructures are too costly to be built by a single National Metrology Institute, it appears impossible to duplicate the traceability chain in each EURAMET country. A key outcome will be to deliver new integrated metrological services for large-scale hydrogen or HENG flow metering as needed by the industry and end user communities.

This project will deliver traceability at the largest flow rate range, directly linked to the requirements of gas network applications, by exploiting two traceable transfer skids (via CFVNs (sonic nozzles) or master meters) up to 1000 m³/h at 6 MPa. The project's outcomes will enable end users to prove their uncertainty claims for pure hydrogen or HENG, using the Integrated European Transfer Standard, at the required < 0.30 % flow rate level (targeted).

Finally, clear statements on the potential transferability of hydrogen calibrations to alternative fluid calibrations will be provided by the consortium based on a solid statistically meaningful measurement dataset. The industrial community will benefit greatly from the technical guidance provided by the expert group, and representatives from industry often express the need to make this dataset publicly available, which will be

done as an outcome of this project. In addition to the realisation of methodologies and recommendations for new/updated standards, this project will also enhance public confidence in the H₂ market by ensuring reliable H₂ metering. Therefore, the outcomes of this project will provide "a small step for the EU Green Deal, but a giant leap for the decarbonisation of Natural Gas grids".

Outcomes for the metrology and scientific communities

The main objective of this project is to deliver new metrological capabilities in Europe. National Metrology Institutes (NMIs) and Designated Institutes (DIs) involved in this project will be able to propose new services to their customers by exploiting the transfer skids developed during this project. The participating NMIs will declare validated uncertainties (targeted at lower than 0.30 %) based on a bootstrapping method that is traceable back to the primary standards for pure hydrogen and blending. The European Reference for Gas Metering (EuReGa) partners are all represented in the consortium, which will lead to ready adoption of the integrated service by the gas flow measurement industry.

The participants with industrial-scale hydrogen and HENG calibration facilities (EnagastSO, DNV, RMA, FORCE) will be able to perform a laboratory intercomparison in this project with the large scale transfer standard to prove their claimed uncertainties.

The outcomes from this project will benefit the metrology and scientific communities by providing a large, meaningful dataset of calibrations with hydrogen, HENG and alternative fluids. Using this dataset, the achievable measurement uncertainty of various flow meter technologies will be determined, and robust guidance will be provided on the efficacy of calibration with alternative fluids. The new knowledge generated will be published in peer reviewed journals.

Fundamental scientific knowledge concerning the underlying flow physics of CFVNs (sonic nozzles) will be obtained by performing calibrations with both hydrogen and nitrogen (at mass flow rates that will be larger than those performed in EMPIR JRP 20IND11 MetHylInfra). The Joule-Thomson effect and the pressure and temperature dependency of the isentropic exponent will be investigated for CFVNs (with a diameter larger than 3 mm).

Outcomes for relevant standards

The consortium comprises experts in flow metering that are deeply involved in numerous national and international technical standardisation groups (ISO, OIML, CEN, WELMEC). Using guidance from EMPIR JRP 18NRM06 NewGasMet, this project aims to demonstrate the transferability of alternative gas calibrations to applications with hydrogen or HENG. Clear conclusions will be drawn, and the outcomes will be transferred to the legal metrology community as input for the modification of existing standards, including those which are under the control of the CEN TC 234 and CEN TC 237 working groups: EN12480, EN12261, EN1359, EN14236 and EN17526.

Longer-term economic, social and environmental impacts

Like natural gas, the successful implantation of hydrogen in energy systems will be underpinned by metrology. Providing good practice and traceability for hydrogen flow measurement will ensure that planned decarbonised gas networks will be able to operate efficiently and that billing, fiscal and custody transfer measurements will be trusted. This will ensure that the public continues to support the transition to net zero carbon dioxide emissions. This will also support the development of the hydrogen industry and a healthier market for providers of hydrogen technologies and services. It will also encourage innovation and new employment opportunities for European citizens. By taking a leading role in these areas, EU member states will benefit, in the longer-term, from greater energy security and they will be better positioned to export these technologies and services internationally.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>



Project start date and duration:		1 September 2024, 36 months
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Project website address: https://xd.adobe.com/view/a1ad4189-2aed-42bb-8862-a16603ce31e8-f4fe/?fullscreen		
Internal Beneficiaries: 1. Cesame, France 2. CMI, Czechia 3. FORCE, Denmark 4. PTB, Germany 5. SMU, Slovakia 6. VSL, Netherlands	External Beneficiaries: 7. DNV, Netherlands 8. EnagasTSO, Spain 9. GERG, Belgium 10. GRTgaz, France 11. RMA, Germany 12. TG, Italy 13. UNIBO, Italy	Unfunded Beneficiaries: 14. Emerson M, Netherlands 15. SICK, Germany
Associated Partners: 16. METAS, Switzerland 17. NEL, United Kingdom		

Publishable Summary for 23IND06 Met4EVCS Metrology for electric vehicle charging systems

Overview

Electrical Vehicles (EVs) are the core of the European Commission's transition plan for the transport sector towards electromobility. The successful integration of EVs requires the deployment of an extensive infrastructure for EV Charging Stations (EVCSS) covering the overall charging needs of the consumers. This project will tackle the challenges of power quality effects on and as a result of EVCSSs, and evaluate the associated losses and reliability of metering under actual on-site conditions. The project aims to cover several charging modes, such as direct DC charging at low and high power, smart charging, and bi-directional charging. The project will support the industry needs through the development of a metrology infrastructure for traceable testing of EV charging systems which remains a major bottleneck at the moment. The project will also provide input to OIML TC 12, WELMEC WG 11, and the European Commission (EC) Working group WgMI E01349 for uptake in their guidelines and regulations which will, in turn, support the EV charging industry through standardisation.

Need

The EC has adopted an ambitious roadmap for a competitive and sustainable transport system by 2050. With the expected integration of EVs, EVCSSs are a key element in electromobility and, therefore, the Alternative Fuels Infrastructure Directive 2014/94/EU took measures to increase the number of standardised EVCSSs. Though EVCSSs may be considered simple meters, additional factors, such as grid distortion and dynamic impedance during charging, challenge their reliable operation. In addition, the detailed characterisation of the effects that EVCSSs may have on the grid will be valuable to anticipate deteriorating Electromagnetic Compatibility (EMC) or Power Quality (PQ). Therefore, there is a need to characterise on-site local grid conditions in various charging scenarios.

The methods and standards applied in existing EVCS test benches do not reflect representative operating conditions. Also, characterisation of newer charging modes, such as DC charging at low power and ultra-fast charging at high power, smart charging, and bi-directional charging, is not well covered in standards.

Therefore, there is a need for establishing EVCS test benches for both DC and AC, implementing new measurement methods and standards reflecting representative operational conditions at low, medium, and high power levels, following IEC 61851-1. These test benches shall be capable of evaluating (i) metering accuracy and energy transfer efficiency with a target uncertainty of 0.1 %, and (ii) generated conducted emissions up to 150 kHz.

Knowing that the number of EVCSSs is growing rapidly, there is a need to develop the metrological infrastructure for on-site verification of EVCS energy metering, in support of legal metrology. On-site verification requires reliable and efficient measurement procedures, based on commercially available equipment capable of handling representative operating conditions and charging scenarios. The uncertainty of the metering accuracy verification is targeted at 0.5 %.

Report Status:
PU – Public, fully open

Publishable Summary

Issued: August 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership

Co-funded by the European Union

METROLOGY PARTNERSHIP

EURAMET

Objectives

The project focuses on the development of metrology capabilities for the traceable evaluation of EVCSs under realistic operating conditions.

The specific objectives are:

1. To define representative on-site operating conditions for EVCSs in terms of local grid disturbances and local grid impedance under live grid operation. For this, dedicated measuring equipment will be developed for measuring local grid disturbances and local grid impedances up to 150 kHz. With this equipment measurements will be performed at, at least, five sites with DC chargers and five sites with AC chargers with a variety of (i) charger brands, (ii) operating modes and (iii) charging power levels.
2. To develop traceable methods and test benches for the characterisation of EVCSs under representative operating conditions for both AC and DC charging in accordance with IEC 61851-1. For AC chargers, the characterisation will be performed at low and medium power, and for DC chargers the characterisation will be done at low, medium and high power. The characterisation involves the evaluation of (i) metering accuracy and energy transfer efficiency with a target uncertainty of 0.1 % (with respect to nominal power) and (ii) generated conducted emissions up to 150 kHz. For AC EVCSs, test benches will be developed for three-phase systems at 230 V up to 100 A and charging power levels up to 44 kW; for DC EVCSs, test benches will be developed for voltages up to 800 V, currents up to 500 A and charging power levels up to 350 kW.
3. To develop the required metrological infrastructure for on-site verification of EVCS energy metering, in support of legal metrology and acceptance testing, with a target uncertainty of 0.5 %. This will include the development of reliable methods for EVCS energy metering evaluation based on commercially available equipment, which have been validated under representative operation conditions, including smart charging and bidirectional energy transfer.
4. To facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (IEC TC 69, WELMEC WG 11, OIML TC 12/p 3, EC WgMI E01349), and end users (e.g., EMN Smart Electricity Grids, EMN Clean Energy, EVCS operators, grid operators, EVCS manufacturers).

Progress beyond the state of the art and results

Definition of representative on-site operating conditions for EVCSs and characterisation of local grid disturbances and local grid impedance (objective 1):

Currently, the most common method of EV modelling is to consider the EV loads as constant power elements without considering the voltage dependency of EV charging systems during the charging process. Several research projects on smart grids are now looking into realistic models representing the realistic behaviour of an EV load to understand the impact of EV charging load, but such models are not yet available nor are the measurement data to support such modelling.

The project will investigate typical EV voltage and impedance patterns as a function of time and state of charge during the charging process, based on on-site traceable measurements at EVCS sites. In some cases, the project will employ an EV load emulator (dummy load) that can simulate these voltage and impedance patterns. The patterns will cover a representative set of the most used EVs, energy transfer modes, and battery capacities.

Development of traceable methods and measurement standards for the characterisation of EVCSs under representative operating conditions for both AC and DC charging (objective 2):

Currently, the characterisation of EVCSs is limited to energy metering based on domestic AC supply meter regulation. Specific aspects of DC metering and aspects of high-power transfer at big charging stations are insufficiently characterised to ensure the reliability of the energy metering and are not fully adequate for estimating the efficiency of the charging stations with sufficient accuracy.

The project will develop the metrological infrastructure for laboratory characterisation of EVCSs including test setups, test methods, test conditions, and reference standards required for traceable characterisation of the energy transfer and energy loss. In some testing scenarios, EV simulators and dummy loads will be used instead of the whole EV. Since facilities for high-power DC charging are still scarce, these will receive extra attention.

Development of metrological infrastructure for on-site verification of EVCS energy metering (objective 3):

OIML TC 12/p 3 has recently produced a guiding document, OIML G 22 “Electric vehicle supply equipment”, but practical technical experience in testing and approving is still lacking in some respects, especially for DC charging applications. Furthermore, its practical implementation is a challenge because some tests require expensive hardware and are very time-consuming. This is not suitable for the fast-growing EVCS market. The project will provide practical technical input to OIML TC 12/p 3 for improvements of the current guide and its successor document on methods for verification of DC and AC EVCSs.

The project will establish the basis for an integrated metrology infrastructure for EVCS metering verification. For this, the project will propose validated simplified test setups and validated simplified test procedures for fulfilling a minimum set of test requirements to verify the EVCS metering accuracy in field conditions.

Outcomes and impact

Outcomes for industrial and other user communities

The project will provide a thorough quantification of high-frequency emissions and distortion caused in the supplying grid, together with feeding an EVCS impedance, improving the knowledge provided by the few existing standards (e.g. IEC TR 60725). This will allow manufacturers to simulate the emissions of their own equipment more accurately, improving the margins to consider during design and production, but also being able to foresee resonance situations for specific grid topologies.

EVCS operators and DSOs can use the results of grid-and-EVCS interaction measurements and modelling for planning a high concentration of EVCSs in the near future. The set of waveforms for distortion and emissions gathered in the project will be evaluated for the influence on metering and losses, providing an indication to many actors (manufacturers, grid operators, consumers) of the cost of distortion as affecting efficiency through losses directly or indirectly through disturbance to metering.

The test benches and test procedures developed in the project for EVCS metering and loss verification will contribute to the lasting metrology infrastructure in the field and provide the various NMIs with testing capabilities to fulfil their market needs. These measurements will help build trust and experience with the technology and further help the EVCS industry, both manufacturers and charge point operators (CPOs), in the widespread deployment of EVCSs. This will also provide guidance as input to the new European legislation on EVCS testing which will in turn facilitate mass production of EVCSs.

This project will provide new insights to the manufacturers and operators on ways to optimise the design of the charging station and emphasise the shortfalls in their current design by investigating the influence of external factors on metering and losses in EVCSs. The outcomes of the project are set to greatly benefit the EV industry and the operators of EV charging stations. The development of a European metrology infrastructure for the verification of the metering and losses in the EV charging infrastructure will further propel the pace of development in the field of EV chargers by reducing waiting times in certification and testing. European consumers will eventually benefit from a good EV charging infrastructure with the added traceability and fair metering of electrical energy. This will increase the level of confidence in the consumers and as a result, support the transition to electromobility in Europe.

Outcomes for the metrology and scientific communities

The test benches developed for the verification of the metering and losses in EVCSs in the various charging modes and the setups and methods for the consistent on-site measurement of EVCSs and EV emissions and distortion by different European institutes will lead to the establishment of an integrated European metrology infrastructure. This upholds the idea of smart specialisation, of an integrated metrology infrastructure of the European area. The devised procedures for the certification and verification are a key step towards the establishment of a common regulation. Knowledge transfer to non-participating NMIs and test institutes will be performed via project workshops and presentations at scientific and industry workshops and conferences.

The project will establish a database for disturbances and impedance measurements that will lead to defining a procedure to evaluate EVCS distortion. For that, comprehensive measurement methods will be defined and validated. Ad-hoc test waveforms, similar to the complex waveforms generated during the EVCS process, will be defined and used to optimise and validate the assessment methods.

The published results in terms of the test waveforms, impedance envelopes, and procedures will serve as a starting point for new and improved research in the field. It is expected that the new measurement and analysis methods, as anticipated, can be reused for similar types of scientific research.

The knowledge of changes in the grid impedance during the EVCS charging will be fundamental for the grid operators to support the impact of EVCS deployment in the near future.

Outcomes for relevant standards

The increased distortion of distribution grids in the near future following the extensive increase of EVCSs and EVs requires revised standards related to PQ issues on public electricity networks. Completing previous results, including the EMPIR JRP 18NRM05 SupraEMI, accurate measurement methods for EVCS disturbances will be proposed for the current standardisation work at IEC SC 77A in relation to the IEC 61000 family standards.

This project will provide three guidelines for metering evaluation and on-site verification of EVCSs to several national and international standard committees dealing with the legal regulation of electricity meters such as IEC and CENELEC TC 13.

Significant input is anticipated for the working groups of OIML TC 12 "Instruments for measuring electrical quantities" for the next revision of the recently published EVSE guide G 22; of WELMEC WG 11 "Utility meters" for the harmonised regulation for EVCSs across Europe through the generated good practice guides.

Longer-term economic, social, and environmental impacts

The wider impact of the project can hardly be underestimated. In general, a harmonised EVCS metrology infrastructure will increase the level of confidence in the consumers and as a result, support the transition to electromobility in Europe.

More specifically, the standards and guidelines resulting from the project will pave the way for a harmonised regulation of EV charging. Such a European or International regulation will have a substantial economic impact as it will enable mass production. Standardised AC and DC metering systems enable international expansion of EV charging networks. They ensure that charging stations can be deployed in multiple countries without significant modifications, fostering the growth of EV adoption worldwide. As EV technology evolves, standardisation allows for easier upgrades and compatibility with new features and improvements. This flexibility ensures that charging infrastructure can adapt to emerging technologies and customer demands. Some of the industries that will benefit from this project are calibration laboratories which provide traceable verifications of the equipment, EV and EVCS manufacturers which will be able to optimise their designs, and EVCS operators that will be able to ensure fair transactions for end users that meet the needs of the European regulatory bodies.

The presence of a reliable EV charging infrastructure with traceable metering is fundamental to the deployment of EVs. This in turn promotes the integration of renewable energy sources which reduces the environmental impact of the energy production process and reduces the dependency on oil and gas.

As an added benefit, the project improves the know-how on metering and losses involved in new and innovative charging modes such as smart charging and V2G charging. These topics are aimed to help mitigate the impact of EVs on grid congestion and reduce electricity generation capacity needs on future grids.

List of publications

No open-access publications have been published yet.

The list will also be available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 July 2024, 36 months
Coordinator: Helko van den Brom, VSL Tel: +31 6 3111 9893		E-mail: hvdbrom@vsl.nl
Project website address: Not available yet		
Internal Beneficiaries: 1. VSL, Netherlands 2. BEV-PTP, Austria 3. BFKH, Hungary 4. CEM, Spain 5. CMI, Czechia 6. JV, Norway 7. LNE, France 8. MIRS, Slovenia 9. RISE, Sweden 10. TUBITAK, Türkiye 11. VTT, Finland	External Beneficiaries: 12. CIRCE, Spain 13. Elaad, Netherlands 14. EMC-BCN, Spain 15. INM, Republic of Moldova 16. INTI, Argentina 17. ITE, Spain 18. SUN, Italy 19. UNIGE, Italy 20. UPV/EHU, Spain 21. UTwente, Netherlands	Unfunded Beneficiaries:
Associated Partners: 22. STRATH, United Kingdom		

Publishable Summary for 23IND07 RadonNET

Radon metrology: Sensor networks for large buildings and future cities

Overview

In compliance with the Directive 2013/59/Euratom, member states are required to mitigate ^{222}Rn activity concentration in public and private buildings, where levels regularly exceed the reference threshold of 300 Bq m^{-3} . Authorities are mandated to implement mitigation strategies that adhere to basic safety standards, safeguarding citizens from ionising radiation exposure due to ^{222}Rn progenies. This project addresses the challenge of quantifying ^{222}Rn activity concentrations indoors, particularly in large buildings for future cities with a focus on connected, low-energy consumption buildings. The development of methods and sensors for detecting radon activity concentration as well as the creation of quality assured sensor network will enhance on-site ^{222}Rn metrology and provide support to the European radiation protection industry.

Need

Reducing air exchange in large buildings offers cost savings, yet encounters resistance due to radiation protection concerns, particularly related to indoor ^{222}Rn activity concentration. As outdoor ^{222}Rn levels are generally lower, efficient ventilation remains a proven technique for mitigating exposure to this radioactive gas. However, ventilation increases energy usage and maintenance costs and should be employed only as much as needed due to indoor air quality and specifically ^{222}Rn activity concentrations. Fluctuations in ^{222}Rn emanation due to temperature, pressure, and humidity variations underscore the necessity of employing smart sensor networks in connected buildings to monitor the changes in ^{222}Rn levels. This technological adaptation is imperative for achieving energy-efficient designs for future buildings.

Despite these advantages, the current state of metrology for connected sensors and networks is insufficient in Europe. Vital for observing ^{222}Rn levels in expansive structures or multiple houses, sensor networks prevent wasteful energy use or overlooking high ^{222}Rn areas. Manual detector maintenance and analysis are labour-intensive, leading to unnoticed malfunctions. Relying solely on a single detector location risks inefficiency or missing regions with high ^{222}Rn concentrations. Furthermore, the calibration of sensors proves expensive and presently inefficient or non-existent for cost-effective sensors.

The solution necessitates the deployment of sensor networks, effectively balancing radiation protection and energy efficiency. The need to safeguard citizens from radiation is acknowledged by the European Directive 2013/59/Euratom which underscores the importance of ^{222}Rn mitigation. Connected radon instrumentation plays a pivotal role in reducing radon-related risks. Networked instruments bolster radiation protection and thus diminish lung cancer risks. Nonetheless, realising the deployment of sensor networks is complex, particularly concerning cost-effectiveness. Overcoming this challenge requires bespoke solutions and the integration of radon metrology and sensor network metrology expertise.

Sensors with long response times and unverified linearity thwart timely mitigation action. The project capitalises on connected technologies to ensure swift response and precise calibration. The main aim is to develop efficient devices that establish the calibration standard for low activity concentrations, reaching down to Bq m^{-3} , in connected buildings. The pursuit of novel sensor techniques, measurement methodologies, and metrological traceability for connected devices and networks is indispensable to position Europe as a front-runner in radon mitigation, all while considering energy-efficient connected building designs.

Report Status:
PU – Public, fully open

Publishable Summary

Issued: September 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



Co-funded by
the European Union

**METROLOGY
PARTNERSHIP**



Objectives

The overall objective of this project is to develop new and to improve, expand and merge existing ^{222}Rn activity concentration measurement sensors to networks that automatically provide regular and reliable indoor ^{222}Rn activity concentration measurements.

The specific objectives are:

1. To develop new concepts and methods for sensors detecting radon activity concentration with lowered response time, increased sensitivity and reduced uncertainty compared to existing solutions. To build the sensors in a cost-effective and material-saving way through advanced manufacturing techniques using industrial production by SMEs. (WP1)
2. To develop traceable, in-situ operando calibration procedures for these sensors with less than 10 % uncertainty at an activity concentration level down to Bq m^{-3} , allowing for response time and dynamic linearity testing. (WP2)
3. To develop a quality assured sensor network suitable for large building monitoring, consisting of the developed sensors and based on the use of artificial intelligence, IoT and a digital twin. (WP3)
4. To develop an extension of the sensor network capable of including other existing and potential building sensor networks that incorporates intelligent data analysis and integration methods to enable the optimised use of energy, air quality management and radiation protection in a single monitoring system. (WP4)
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the industry, the measurement supply chain (NMIs, calibration laboratories), the standards developing organisations (e.g. IEC, ISO), end users in radiation protection and building air quality system manufacturing and via the EMN on Radiation Protection, to support the development of new, innovative products, thereby enhancing the competitiveness of EU industry. (WP5)

Progress beyond the state of the art and results

New methods and sensors for detecting radon activity concentration (objective 1)

Currently, there are numerous radon detectors available, both passive and active. However, many of these are based on outdated models and aging technology that have undergone various ownership changes between companies. Their primary drawback often lies in their cost, particularly for active detectors, and the fact that they are not IoT devices capable of enabling active radon mitigation.

By leveraging advanced manufacturing techniques, RadonNET aims to create next-generation prototypes of connected sensors that will not only be cost-effective and material-saving but also surpass the performance of existing ^{222}Rn detection devices. These future sensors will exhibit significantly lowered response time, be compact and network-connected for remote measurements with unparalleled sensitivity. These properties will contribute to a significant reduction in measurement uncertainties for the targeted concentration limit of 300 Bq m^{-3} given by the Directive 2013/59/Euratom. The development will focus on producing the sensors in a cost-effective way to enable technology transfer to SMEs in Europe. The sensor connectivity will enhance the radon mitigation and cost calibration by proposing new features in the metrology domain such as network calibration and type testing.

New in-situ operando calibration procedures for sensors (objective 2)

Radon instrument calibration is conducted in laboratories using primary standards and dedicated exposure chambers. While this method can be highly precise when properly executed, it may not be suitable for certain needs, particularly due to its high operational costs, especially for low-cost detectors. Additionally, it requires transporting the devices to calibration laboratories, making it incompatible with active radon mitigation.

RadonNET's vision includes achieving traceable in-situ operando calibration with the development of new, innovative measurement devices and primary measurement methods that will be developed to calibrate connected radon sensors. Operando calibration of a connected network of sensors will make it possible to avoid immobilising equipment and will limit the costs associated with calibration, making Europe the leader in this domain. The targeted measurement uncertainties are less than 10 % at an activity concentration level of Bq m^{-3} , six times lower than the normative limits to ensure reliable results, avoid false alerts and move closer to the recommended value of WHO at 100 Bq m^{-3} . Methods incorporating dynamic linearity testing and sensor

response time optimisation will be developed. These new calibration procedures will transcend current capabilities and incorporate the measurement of sensor time response, which is missing from current calibration procedures. This change in the field of metrology will provide unprecedented precision in radon metrology and enhance radon mitigation in connected house while saving energy. The new calibration methods will be usable for other radioactive gases (e.g., ^{133}Xe , ^{85}Kr , ^3H , and ^{37}Ar), offering an impact beyond the scope of this project and enabling precise measurements of radioactive gases, which is of major importance for future developments in nuclear power generation, such as Small Modular Reactors (SMRs).

Quality assured fit-for-purpose sensor network (objective 3)

There is currently no network of radon sensors, despite the existence of current technologies for pollutants such as VOCs, CO_2 , or even more recently, aerosols. This absence prevents active radon mitigation, even though all current IoT systems allow for it.

This project envisions the development of an intelligent sensor network that will revolutionise large building monitoring and environmental control. This visionary sensor network will seamlessly integrate artificial intelligence and IoT, ushering in a new era of sophisticated and interconnected air quality monitoring systems.

Extension to include other sensor networks (objective 4)

Radon sensors are often paired with pressure, temperature, or humidity probes, mainly to correct the displayed values based on the device's operation. However, these data are not generally used both for measuring and actively mitigating radon.

By incorporating the measurement of indoor ^{222}Rn activity concentration, this new network will enable the optimisation of energy use, air quality management, and radiation protection in a unified and intelligent manner, shaping the future of smart and sustainable cities with limited energy consumption. RadonNET will forge essential recommendations and guidance specifically tailored to radon metrology. RadonNET's advancements will also lay the groundwork for the incorporation of radon calibration and mitigations measures into the design of connected homes. This approach is groundbreaking, aligning indoor air quality, radiation protection, and overall well-being with the principles of future-oriented living environments.

Outcomes and impact

Outcomes for industrial and other user communities

Enhanced Safety and Health Measures: The project's development of advanced radon activity concentration sensors and traceable calibration procedures will empower industrial and user communities, such as building managers, regulators and authorities, construction companies, and homeowners, to implement more effective safety measures. With accurate real-time data on radon levels, these communities can proactively mitigate radon exposure risks and ensure healthier indoor environments, reducing the incidence of lung cancer associated with radon exposure.

Cost-Effective Sensor Networks: The project's focus on cost-effective, material-saving prototype sensors and automated data acquisition and transmission will result in sensor networks that are affordable and easily deployable for large buildings and future cities. This outcome will benefit industrial stakeholders, such as property developers and facility management companies, by offering cost-efficient solutions for implementing radon monitoring systems in various structures without significant extra financial burden.

Improved Energy Efficiency: The integration of radon sensor networks with other building sensor networks and the use of artificial intelligence will enable energy-efficient regimes for air exchange systems. Industrial communities will benefit from reduced utility costs in large buildings, as energy-saving approaches are optimised without compromising indoor air quality and radiation protection.

Market Opportunities for Sensor Manufacturers: The project's focus on strengthening European ^{222}Rn measurement manufacturers by developing new sensor technology and supporting regulations will create market opportunities for sensor manufacturers. With the increased demand for innovative, sensitive, and reliable radon sensors, manufacturers can expand their product portfolio and tap into a growing market for radon detection solutions.

Outcomes for the metrology and scientific communities

Advancements in Radon Metrology: The project's research and development of novel radon activity concentration sensors and calibration procedures will significantly advance radon metrology. The metrology

community will benefit from new insights into radon detection techniques, improved measurement uncertainties at low concentration levels, and enhanced traceability of radon activity concentration measurements. The core of the project will be focused on in-situ operando metrology of connected measurement devices. The project will significantly improve existing strategies for radon sensor network calibration and develop necessary devices and methods to make the calibration more cost-effective.

Collaboration and Knowledge Exchange: The project's collaborative and international nature, involving multiple stakeholders, universities, and SMEs, will foster knowledge exchange within the metrology and scientific communities. Researchers and experts in radon metrology will share their expertise, methodologies, and best practices, leading to mutual learning and the advancement of the field. Although the project is primarily dedicated to ionising radiation, it will also directly connect with recent calibration work for sensor networks, especially in other quantities such as pressure, temperature, humidity, and any other measurements required in connected buildings.

Validation of Emerging Technologies: The project's validation of emerging technologies, such as artificial intelligence and IoT, and new methods for radon sensor calibration networks will serve as a valuable reference for the scientific community. The results and findings can be used to inform future research and applications in other fields of radionuclide metrology and environmental monitoring. The new sensor and calibration methods of sensor networks developed in this project could be used for other radioactive gases, particularly those measured for monitoring Evolutionary Power Reactor (EPR1 & 2), future emerging SMRs, and future fusion reactors, as well as in waste treatment monitoring.

Student Formation and Knowledge Transfer: The project's collaborative nature and involvement of SMEs and universities will provide valuable opportunities for student formation in the scientific communities. Students will have the chance to engage in cutting-edge research, gain hands-on experience in radon metrology and sensor network metrology, and work alongside experts, fostering knowledge transfer and nurturing the next generation of metrology professionals.

NMIs and DIs that are not participating in the project will be involved as collaborators, and their knowledge and installations will be used where appropriate (e.g., CIEMAT, STUK, FTMC, KRISS).

Outcomes for relevant standards

Improved Standardisation of Radon Metrology: The project's development of traceable calibration procedures and quality-assured sensor networks will contribute to the standardisation of radon metrology. By aligning with international standards organisations such as International Electrotechnical Commission (IEC) and International Organisation of Standardisation (ISO), the project's outcomes will influence the establishment of standardised protocols for radon detection and monitoring and can be extended to other radioactive gases as well.

Guidelines for Radon Mitigation Strategies: The project's research on radon monitoring for large building will provide valuable insights for the formulation of guidelines and standards related to radon mitigation. Regulatory bodies and standard-setting organisations can use this information to develop effective measures to reduce radon exposure in buildings.

Longer-term economic, social and environmental impacts

Public Health Benefits: The project's focus on improving radon detection and implementing mitigation strategies will lead to reduced incidences of radon-related lung cancer, improving public health and reducing mortality rates in radon-prone areas. Lower healthcare costs associated with radon-induced health issues will benefit European healthcare systems and society as a whole.

Improved Indoor Air Quality: By enabling the implementation of advanced radon sensor networks, the project will contribute to improved indoor air quality in large buildings and future cities. Cleaner and healthier indoor environments will positively impact the well-being and productivity of occupants, leading to a healthier society.

Energy Conservation: The integration of radon sensor networks with energy-efficient air exchange systems will lead to energy conservation in large buildings. Reduced energy consumption will contribute to environmental sustainability by lowering carbon emissions and mitigating the impact of buildings on climate change.

Market Growth and Job Creation: The expansion of the radon metrology market and the rising demand for radon sensors will energise economic growth in the EU. This surge will result in job creation across various



sectors, including sensor manufacturing, technology advancement, and the establishment and upkeep of radon monitoring systems. Furthermore, the radon mitigation industry stands to gain significant momentum from the introduction of highly sensitive radon-calibrated sensor networks, a sector that is more advanced in the USA than in Europe.

Empowering the Workforce: By encouraging student support and involvement, the project will contribute to empowering the future workforce in the field of metrology and environmental monitoring. The expertise gained by students during the project will equip them with valuable skills and knowledge, enhancing employability and addressing the growing demand for skilled professionals in environmental safety and health sectors.

Overall, the outcomes of RadonNET will have far-reaching effects on various communities. The improvements in radon detection, safety measures, and indoor air quality will promote public health and safety. Furthermore, advancements in metrology and scientific knowledge will drive innovation in the field, while adherence to relevant standards will ensure consistency and reliability in radon measurements. The longer-term economic, social, and environmental impacts will contribute to a sustainable and resilient future for European cities and communities.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2024, 36 months
Coordinator: Benoit Sabot, CEA		Tel: +33 0169084652
Project website address: http://radon-network.eu/		E-mail: benoit.sabot@cea.fr
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CEA, France	6. CLOR, Poland	-
2. BFKH, Hungary	7. IFIN-HH, Romania	
3. CMI, Czechia	8. LivAir, Germany	
4. PTB, Germany	9. NUVIA, Czechia	
5. SMU, Slovakia	10. Radonova, Sweden	
	11. SUBG, Bulgaria	
	12. UCBL, France	
	13. UH, Finland	
	14. USIEG, Germany	
Associated Partners: 15. NPL, United Kingdom		

Publishable Summary for 23IND08 DI-Vision

Traceable machine vision systems for digital industrial applications

Overview

Machine vision systems are crucial to many high-value industries, where Europe is globally competitive, and to the EU objectives for digital transformation and the Green Deal. However, further work is needed to develop digital twins for these systems based on data and physical driven models and the implementation of robust matching and evaluation algorithms for recorded raw data. This will enable the accurate classification of defects or the extraction of geometrical parameters from the surface. In addition, traceability for these systems is also required. The tools developed in this project, combined with uncertainty evaluation methods, will be applied throughout industrial applications on macro- and microscale specimens in order to reach better accuracy, productivity and flexibility as well as improved safety and cost efficiency.

Need

The global Machine Vision market size was valued at 13.23 B€ in 2021 and it is expected to expand at a compound annual growth rate of ~7 % from 2022 to 2030, with Europe accounting for about one-third of the total market revenue share. The rapid growth and innovation in Machine Vision Systems (MVSs) has brought a wave of industrial applications in many manufacturing sectors (e.g. aeronautic, pharmaceutical, medical, electronics, semiconductors). For quality control, MVSs use cameras and sensors to analyse images, to monitor the quality of the product, and to report in-process deficiencies in quasi real-time. The deployment of Traceable-MVSs is perfectly aligned with zero-defect manufacturing and zero-waste ambitions. The intensifying need for superior inspection and increasing automation are the key influencing factors paving the way for the notable adoption of MVSs. The need for increased quality control by consumers and manufacturers, coupled with government regulations to abide by the prescribed specifications, is expected to catapult the future use of MVSs.

As the quality assurance and inspection segment held the largest revenue share of over 50 % in 2021, the availability of a traceable metrology for MVSs becomes indispensable for digital transformation in the Industry 4.0 strategy (a pillar of the EU Green Deal). Currently, calibration methods, including the measurement uncertainty of known influence factors, and approaches to identify additional contributions to the measurement uncertainty are still lacking. These are essential to optimise performances, allow validation, and to ensure metrologically reliable results, which could be enhanced through DTs based on physical or/and data AI-driven models. Nevertheless, the number of contributors addressed, and the methods used for their inclusion in Digital Twin (DT) models are currently very limited. For every developed DT, verification and validation are fundamental.

The published ISO10360-13:2021, has taken inspiration from the VDI/VDE 2634, and it addresses the traceability of optical 3D Coordinate Measuring Machines. This normative standard uses two spheres, which are traceable to the unit of length, the metre. Nonetheless, material standards with prismatic and complex shapes, which would be better related to industrial needs, are lacking. To support the implementation of ISO10360-13, additional materials standards need to be developed, which will provide traceability to MVS (objective 1) with validated DTs for assessing systematic errors and determining robust measurement uncertainties (objective 2). In addition, reference dense matching algorithms are needed for merging recorded images into one coordinate system (objective 3). To support the dissemination of this project's results, industrial use cases related to dimensional, structural, surface and operational qualities and best practice guidance, and user training, seek to reinforce the deployment of MVS in Industry 4.0 processes (objective 4).

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: September 2024

Objectives

The overall aim of this project is to generate traceability for the Machine Vision Systems (MVSs) that are deployed in industrial applications including macro- and microscale products based on the development of traceable material standards, V-DTs, uncertainty evaluation methods, robust and reliable dense-image matching algorithms, as well as robust classifiers and analysing algorithms.

The specific objectives of the project are:

1. To establish the traceability of existing and newly developed industrial MVSs used in (i) dimensional quality, (ii) surface quality, (iii) structural quality, and (iv) operational quality including the development of appropriate material standards with canonical and complex shapes, calibration strategies, traceable identification of MVSs parameters, and uncertainty budgets (target uncertainty $1\ \mu\text{m}$ - $150\ \mu\text{m}$ dependent on MVS application area).
2. To develop Digital Twins (DTs) of selected and newly developed MVSs through physical modelling and/or computational modelling, and to then (i) predict their responses in analysing systematic errors, and to (ii) obtain an optimal measurement strategy in the shortest cycle time. In addition, to develop approaches for the validation of these DTs that include robust methods (e.g., softgauges), and statistical procedures for the assessment of differences between measurements of calibrated standards and corresponding data from their virtual counterparts.
3. To investigate and evaluate novel methods and algorithms for dense image matching (coarse and fine image alignment) of multiple recorded images using 'softgauges' (reference data). The algorithms will use external knowledge (e.g. physical markers, contactless tracking systems, precise positioning systems, intrinsic features of the scene) and filtering processes will be considered. Additionally, robust algorithms will be developed and validated for analysing the full 3D reconstruction and uncertainty budgets compiled.
4. To investigate the outputs and outcomes developed in this project while addressing industrial use cases related to dimensional, structural, surface and operational qualities. In addition, the performance of selected traceable MVSs for industrial applications will be tested on industrial freeform artefacts in a round robin comparison exercise. Based on measurement results, training material and a GPG for T-MVS performance assessments (e.g. dimensional, structural, surface and operational qualities) will be produced.
5. To facilitate the take up of the technology, good practice guides and measurement infrastructure developed in the project by the EMNs MathMet, TraceLabMed, AdvManu, the measurement supply chain, standards developing organisations (ISO/TC213 and ASTM), and end users (manufacturers from the automotive, food, pharmaceutical, etc. sectors). This includes demonstrations of the practical application of the developed technology in multiple industrial applications (e.g. automotive, aeronautic, pharmaceutical).

Progress beyond the state of the art and results

- *To establish the traceability of existing and newly developed industrial MVSs used in (i) dimensional quality, (ii) surface quality, (iii) structural quality, and (iv) operational quality with target uncertainties in the $1\ \mu\text{m}$ - $150\ \mu\text{m}$ range dependent on MVS application area. (Objective 1)*

Manufacturers express the performance of MVSs in various non-uniform ways in order to identify the capability of capturing a real scene. Therefore, only a limited number of NMIs/DIs and research laboratories have been developing protocols for verifying such performance. Ranging from the recent ISO 10360-13:2021, VDI/VDE 2634 to the ASTM, the state of the art about the characterisation of MVSs, with special emphasis on the measurement uncertainty, accuracy and resolution, is in the initial development stage. Most of the proposed protocols are based on well-known objects with canonical shapes. Here, the existing general concept of "measurement traceability" adopted in the field of tactile 3D measurements is usually applied, even if it is inappropriate for 3D imaging. It is a limited view of the complexity of the whole problem because all contributions to the measurement uncertainty must be analysed with respect to the GUM. This requires the development of supplementary material standards with prismatic and/or complex shapes to guarantee the traceability of MVSs when used on similar industrial shapes including both macro- and micro-scale structures.

- *To develop validated Digital Twins (DTs) of selected and newly developed MVSSs and to then (i) predict their responses in analysing systematic errors, and to (ii) obtain an optimal measurement strategy in the shortest cycle time. (Objective 2)*

DTs of the investigated MVSSs from Objective 1 will be implemented by the participants. The identification of the DTs' parameters will be carried out using commercial and/or developed traceable material standards. Softgauges will be developed for validating the implemented DTs and uncertainty evaluation, such as Bayesian or Monte Carlo approaches or documented JCGM-GUM, will be established for them. The V-DTs are essential to correct the errors, while reducing the measurement uncertainty of the investigated MVSS.

- *To investigate and evaluate novel methods and algorithms for dense image matching (coarse and fine image alignment) of multiple recorded images using 'softgauges' (reference data). (Objective 3)*

Image matching is of central importance to a large number of practical applications. Consequently, methods for image matching are increasingly available and could be classified according to the used primitives, i.e. image intensity patterns or features, leading to area-based matching or feature-based matching algorithms. Currently, the image-matching problem is partially solved using stereopairs or via the identification of correspondences in multiple images. Most of the proposed matching methods are based on similarity or photo-consistency measures, while comparing the pixel values between the images. The algorithm developments have always been accompanied by accuracy assessment studies, usually carried out on surface model generation, by comparing the results achieved to a reference dataset. The establishment of a reference dataset with an accuracy which is two to three times better than the expected matching results is not a straightforward task. The metrological and reliability aspects of the resulting 3D measurements and modelling should not be ignored, particularly when targeting highly accurate 3D modelling and visualisation. To this end, clear accuracy robust statements, benchmarking and evaluations must be carried out.

- *To investigate the outputs and outcomes developed in this project while addressing industrial use cases related to dimensional, structural, surface and operational qualities including performance evaluation of selected traceable MVSSs for industrial applications. In addition, training material and a GPG for T-MVSS performance assessments will be produced. (Objective 4)*

The developed calibration procedures of MVSSs, materials standards, validated DTs for MVSSs, uncertainty evaluation methods, reference datasets and reference algorithms will progress beyond the state of the art as they will be applied in 13 case studies covering different industrial applications (automotive, aeronautic, pharmaceutical, medical, semiconductors, nuclear and energy) in close collaboration with industrial participants and stakeholders. Where appropriate, existing software tools in open access will be extended and validated on reference datasets. Guidance will be given on the practical applicability of the developed methods when applied to other industrial case studies. The GPGs and technical reports will be drafted in close collaboration with the industrial participants and stakeholders for each of the different applications. Results will be disseminated within the EU industry as identified by the EMN AdvManu, EMN MathMet, EMN TraceLabMed, CCL, TC-L and ISO communities.

Outcomes and impact

Outcomes for industrial and other user communities

This project paves the way for a broader exploitation of T-MVSSs, combined with V-DTs, software and improved uncertainty evaluation methods, which is crucial for the digitalisation of industry. The harmonisation of multiple developed approaches facilitates the mutual recognition of T-MVSSs and this will help in transferring the outcomes of the project from NMIs/DIs to industrial stakeholders, while addressing identified issues. Industries that give automation preferences are gaining a strategic advantage over peers with supplementary benefits realised from T-MV tools, which will guarantee future economic prosperity in Europe. This will provide the basis for gaining traceability in several metrological applications, where MV and DTs are employed. In the long term, this will lead to a reduction in production time, to better surface quality of manufactured parts, to the "right first time" manufacturing and production of parts and systems, to miniaturisation and to the development of new products, whilst boosting European industry worldwide.

Outcomes for the metrological and scientific communities

New traceable services at NMIs/DIs: Knowledge transfer from experienced NMIs to those less experienced in how to use new types of instrument based-MV will be very beneficial. It will help to raise their knowledge

and measurement capabilities, promote consistency in MV metrology, and provide novel metrology tools that are compatible with the ongoing industry digitalisation progress. Therefore, European NMIs/DIs (e.g. GUM and UM) and accredited laboratories will set up services based on agreed best practices, and new knowledge on T-MVSs, without the associated costs of developing new capabilities. On a broader scope, the project will strengthen the collaboration between NMIs/DIs and will increase their competitiveness outside Europe. The project's results will also help to cope with several EURAMET-EMN strategic road maps.

Health, pharmaceutical and food science communities: In medicine, the use of Traceable-Hyper Spectral Imaging (T-HSI) combined with DTs facilitates and enhances patient-specific diagnosis and the treatment of diseases at earlier stages. It may offer predictive potential for predetermining the prognosis of acute therapeutic responses within clinical uncertainty. Traceable inspection systems for pharmaceutical containers are key for the safe use of drugs. Further, T-HSI significantly improves the ability to identify and detect various chemical constituents, e.g. fruits, to distinguish between rotten and fresh food.

Photonics & other scientific communities: The outputs (reference algorithms, reference data, reference material standards and T-MVSs) and this project's deliverables will help the optical scientific community to make use of the project's advancements and benefits to their research, e.g. concerning the need for highly accurate alignment of the electron beam in lithography, synchrotron, etc.

Outcomes for relevant standards

The consortium will promote the results of the project within the standardisation community: ISO/TC213 (WG2, WG4, WG10 (recently published the ISO 10360-13:2021), WG14, WG15, WG16, WG18, AG12). Further, several participants are active in the ISO/IEC/JTC1/SC41 Digital Twins, which delivers the following standards ISO/IEC 30141, ISO 30172 TR, ISO 30173, ISO 30186, ISO 30188, ISO 30178, etc. The consortium is also connected with the ISO/IEC/JTC1/SC24 Computer graphics, image processing and environmental data representation.

In addition, participants contribute to the ASTM-E57 technical committee, EUSPEN International Scientific Committees, ASPEN Committees, International societies for optics and photonics SPIE and OPTICA, IMEKO technical committees (TC1, TC2, TC10 and TC14), prestigious CIRP Scientific Technical Committees Dn, P and S as well as the European Technology Platform Photonics21. The outcomes will also be communicated, presented and discussed within the EURAMET TC-L and BIPM-CIPM CCL committees during the organised meetings, as well as to the EURAMET EMN MathMet, EMN TraceLabMet and EMN AdvManu. The EMVA, EIT Manufacturing and EFFRA *made in Europe* will be kept informed, therefore disseminating the knowledge further.

The participants of the project are also active in the JCGM WG1, which has the responsibility for the JCGM:GUM and its supplements.

Longer-term economic, social and environmental impacts

The improved capabilities provided by this project will speed-up digital transformation in all industrial production sectors. In the mechanical industry, the adoption of T-MVSs in manufacturing, assembly, bin-picking, etc. processes will reduce the number of iteration steps required in design, production, and testing. This will lead to a drastically reduced production time and cost per individual part or system. The improvements in the reliability, efficiency, and speed of production processes will lead to significant waste reduction, better use of materials, to a decrease in the scrap rate and it will reduce energy consumption, therefore helping to reduce Europe's CO₂ footprint.

Positive social effects will result from the impact of high-end components on the production of new technology components, mobile electronics, medical devices, etc. Better mechanical alignment through new 3D MVSs integrated robot scanning tools or photogrammetry will be used in advanced particle beam therapies resulting in treatments with higher cure rates. In the medical and pharmaceutical sector, the project's outcomes will provide accurate medical devices through systematic inspection, earlier diagnosis of cancer tissue by traceable hyper-spectral imaging (T-HIS), and food quality detection. In the energy industry, the adoption of T-MVSs will help in developing efficient renewable systems and drastically reducing the loss of electrical energy.

List of publications

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 September 2024, 36 months
Coordinator: Prof. Hichem NOUIRA, LNE Tel: +33(0) 140 43 37 63 E-mail: hichem.nouira@lne.fr		
Project website address: -		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. LNE, France	9. IGN, France	15. Brevetti-CEA, France
2. CMI, Czechia	10. POLITO, Italy	16. CERN, Europe
3. CNAM, France	11. TEKNIKER, Spain	17. CETIM, France
4. GUM, Poland	12. UNIPD, Italy	18. FormFactor, Germany
5. INRIM, Italy	13. UPHF, France	19. GE AVIO, Italy
6. UM, Slovenia	14. WUT, Poland	20. GEOMNIA, France
7. VSL, Netherlands		21. Ponsse, Finland
8. VTT, Finland		22. TTPU, Uzbekistan
Associated Partners:		
23. FU, China		
24. PolyMtl, Canada		
25. POLYU, Hong Kong		
26. SwanU, UK		



Publishable Summary for 23IND09 MaritimeMET

Metrology for green maritime shipping: Emission control through traceable measurements and machine learning approaches

Overview

The maritime shipping sector is seeking to embrace alternative fuels such as green ammonia, hydrogen, synthetic fuels, and Power-to-X (PtX) solutions like methanol and biomethane to reduce their environmental impact. This transition demands the development of engine technologies to adapt to these new fuels and a growing need for accurate and traceable measurement systems to support these advancements and validate their performance. Accurate pressure, temperature, and emission concentration measurements are essential for research and development in this sector, and at the same time, benefit related sectors. This project will advance the methods and techniques to control and monitor engine emissions through traceable measurements of pressure, temperature, and emission compositions and apply them in real-world maritime applications. The project will exploit the advances in machine learning approaches and modelling to optimise the power units and exhaust after-treatment systems significantly.

Need

In July 2023, the International Maritime Organization (IMO) revised their 2018 strategy (MEPC 73) target to reduce emissions further through a commitment to ensure the uptake of alternative zero and near-zero greenhouse gas (GHG) fuels by 2030. To achieve this, metrological support is needed to accelerate the deployment of sustainable fuels like methanol, dimethylether, and ammonia in this sector.

Currently, the sector requires traceable measurements of emission components according to the International Convention for the Prevention of Pollution from Ships (IMO MARPOL), Regulations 13 and 14. There is an inherent need to ease the availability of traceable standards, check the compatibility and ability of existing and new emission monitoring techniques to accurately measure pollutants from future fuels, along with a better understanding of instrument characterisations and their uncertainties (i.e., span drift, instrument linearity, and cross interferences). Calibration of measurement systems using gas standards (required below 2 % uncertainty) can be substituted by spectroscopy-based techniques. However, these are only established for specific species (e.g. NO₂) at limited pressure, temperature, and gas matrix operating conditions and must be explored for existing and new species relevant to future fuels (Objective 1).

The transition to renewable energy carriers necessitates further engine system development and retrofitting of existing power units and after-treatment systems. These activities require traceable measurements of dynamic pressure and temperature at engine operating ranges to monitor and optimise the in-cylinder processes for efficient operation. The dynamic sensors used for this purpose are quasi-statically calibrated, which can lead to significant uncertainties and require traceable measurement methods (Objective 2).

Engine manufacturers require accurate sensors with traceable measurement methods to reduce uncertainties during the R&D phase and for ensuring optimal control of engines during commercial operation. There is a need to increase the reliability of low-cost sensor data deployed in different engine systems through machine learning approaches. However, machine learning models require large amounts of accurate and traceable data. The combined needs must be addressed through testing low-cost and high-quality sensor techniques in application test benches, and in the process, this can lead to exploring cost-effective virtual sensor concepts (Objective 3).

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: September 2024

Objectives

The overall objective of the project is to provide metrological references for emission parameters, dynamic pressure, and temperature through traceable measurements on a system level that benefit the maritime sector, and to develop novel, innovative solutions and technologies that serve the industry and society.

The specific objectives are:

1. **To develop new and improve existing traceable emission measurement methods for online and in-situ measurements of typical gaseous** (e.g., NO, NO₂, N₂O, NH₃, CH₃OH, CO, CH₂O) and PM, black carbon (BC) emissions generated with the use of Power-to-X (PtX) fuels (e.g. methanol, dimethylether, ammonia). The methods and selected commercial low-cost sensors will be validated and applied for dynamic measurements in industrial environments such as test engines running on selected fuels. Sources of measurement uncertainties will be identified and quantified. Measured quantities will be used in predictive model developments using machine learning tools.
2. **To establish quality-assured dynamic measurements of the in-cylinder dynamic pressure and temperature** necessary for assessing and optimising the quality and efficiency of the energy conversion processes using renewable fuels. This will be achieved by developing primary standards and robust measurement methods covering the 0.1 MPa - 30 MPa pressure range and up to 2500 °C range in temperature. The frequency ranges of 0.5 kHz - 100 kHz and up to 1 kHz in pressure and temperature, respectively, with an uncertainty of 1 % will be targeted. An inter-laboratory comparison and engine tests will validate the developed standards and methods. The results will be used in the predictive model development.
3. **To create predictive models for engine emissions and performance using chemical kinetics and machine learning.** Furthermore, **virtual sensor concepts will be developed based on data-driven and physics-based models** to estimate hard-to-measure quantities or substitute costly sensors. Emission measurements (objective 1) and in-cylinder pressure and gas temperature (objective 2) will deliver the required database for model development, a mandatory input to complete these objectives. All models will be validated, and uncertainty estimations will be done.
4. **To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain** (e.g. accredited laboratories, instrument manufacturers), standards developing organisations (e.g. ISO, CEN/CENELEC), end users (e.g. marine, power and aviation industries), and via the European Metrology Networks (such as Energy Gases, Pollution Monitoring, Climate and Ocean Observation, and Mathematics and Statistics).

Progress beyond the state of the art and results

Developing new and improved traceable emission measurement methods for online and in-situ measurements of typical gaseous (e.g., NO, NO₂, N₂O, NH₃, CH₃OH, CO, CH₂O) and PM, black carbon (BC) emissions generated with the use of Power-to-X (PtX) fuels (e.g. methanol, dimethylether, ammonia).

Even though many of the pollutants mentioned and their measurement techniques have been investigated in previous projects (16ENV05, 16ENV07, 16ENV08, 19ENV09 MetroPEMS, 16ENV02 Black Carbon, IMPRESS2), they have not been rigorously tested in dynamic environments typical for the shipping sector. Moreover, the techniques have often been validated against single molecules at limited pressures and temperatures, and the exhaust gas composition from future fuels could lead to interference effects in the pollutant measurements that have not been well quantified. Therefore, pollutant measurement techniques and their operation principles must be studied and validated for accuracy and reliability, specifically in the shipping sector. The optical gas standard (OGS) proposed in previous projects based on the spectroscopy principles will be tested against the reference gas standards for deployment in the maritime sector. OGSs can potentially complement or substitute reference gases in the field where continuous measurements and calibration are required for the long term. As methanol and ammonia are the next generation of fuels commonly suggested for this sector, the related pollutants and fuel slip are of interest, especially nitrous oxide (N₂O) and formaldehyde (CH₂O), the latter being unregulated. For methanol engines, it is observed that there is an increased formation of formaldehyde in the exhaust gases. New spectroscopic-based traceable methods will be developed and explored in engine validation tests. Additionally, a selection of low-cost commercial sensors available in the market for the marine industry will be compared and characterised against the primary

standards available in the project. A report on the uncertainty analysis will be available for the industry stakeholders and the metrology community.

Establishing calibration standards and measurement methods to ensure traceability for dynamic pressure and gas temperature.

Previous projects (EMRP IND09 Dynamic and EMPIR 17IND07 DynPT) have taken the initiative to establish the metrological infrastructure that addresses pressure and temperature ranges similar to those in this project. However, the two calibration techniques developed for dynamic pressure operated at different frequencies (i.e., < 1 kHz for impact mass and 0.5 kHz - 100 kHz for shock tube). The reported uncertainties were around 2 % between 5 MPa - 30 MPa for the impact mass technique while, the uncertainty for the shock tube technique was even higher at about 5 %. The need from the industry is to reduce the uncertainty to 1 %. Several steps, like extending the measurement frequencies, performing cross-comparison of the two techniques, and understanding the influence of non-linearities and dynamic effects through numerical and experimental investigations are planned to better understand the impact of the sensor and the calibration techniques. On the dynamic temperature aspect, non-contact-based sensors were developed with 3 % uncertainty in a similar temperature range, and they will be further improved in this project. Further development of these sensors and techniques is planned through a fibre-optic spectrometer with a 250 kHz sample rate and three different frequencies. It will also be characterised by a laser-based radiance facility for its spectral performance and response time. Thermal imaging techniques will be deployed for developing and implementing traceable calibrations up to 2500 °C. Additionally, absorption spectroscopic techniques used in chemical kinetic studies will be explored in the temperature range up to 1500 °C, frequency between 5-10 kHz, and target uncertainties of 1 %. In-cylinder measurements are also planned in the engine using the fibre-optic spectrometer and Ultraviolet / Infrared (UV/IR) spectroscopy.

Creating predictive models for engine emissions and performance using chemical kinetics and machine learning, with developing virtual sensor concepts based on data-driven and physics-based models.

Different approaches to model engine emissions and key parameters will be explored in this project due to the availability of engine validation tests performed as part of the first two objectives. First, predictive models for exhaust after-treatment systems will be undertaken using stand-alone models or a combination of physical and data-driven approaches. A second approach will utilise data from chemical kinetic mechanisms along with GT-Power engine simulation software while validating the engine parameters and emissions obtained from the engine tests. Additionally, a detailed uncertainty evaluation of both approaches will be performed to better understand their capabilities and boundaries. In addition, machine learning methods will be extended to virtual sensors. Unlike conventional physical sensors, which record physical phenomena directly, virtual sensors leverage existing physically measured data to infer the values of desired parameters. The validation measurements on the engine and calibration information from low-cost sensors will be utilised to model parameters of interest (e.g. knock, cylinder pressure, emission parameters).

Outcomes and impact

Outcomes for industrial and other user communities

The project will develop traceable emission measurement methods, new sensors to monitor pollutants from the current exhaust, and future engines operating on low-carbon or nitrogenated fuels. The implementation of future fuels in the marine sector is in its infancy. The outcomes of this project will help in future research, development, and implementation phases by ensuring accurate measurement techniques are reflected in products and sectors. Developing compact online sensors to monitor possible fuel slip (e.g., methanol, ammonia) will help in closed-loop engine control and potentially lead to new spin-off developments such as new sensors and instruments. The project will also develop primary standards and measurement methods for dynamic pressure and temperature covering a range of 0.1 MPa - 30 MPa in pressure and up to 2500 °C range in temperature, with a target uncertainty of 1 %. Such conditions benefit the chemical engineering, aviation, energy, and space industries, where the thermo-chemical conversion process is much more dynamic and critical. Additionally, it will establish capabilities for national and accredited laboratories in Europe and support consistency in measurement methods.

Characterising low-cost commercial sensors for emission measurements in new environments and commercially available pressure sensors against primary calibration standards and performing cross-comparative measurements in application test beds will help the industry and sensor manufacturers

understand the sensors and improve them for further applications. Furthermore, this project will provide the perfect mix of industry, metrology, and data sciences, to establish approaches that could benefit them all. The concept of virtual sensors depends mainly on inferring desired parameters through the measurement data of existing physical sensors. However, the accuracy of the transfer functions would largely depend on the accuracy of the physical sensor and with insights into low-cost sensor characterisation study, the reliability of the virtual sensor concept can be enhanced and used in the sector and other industries.

The outcomes from the project will be disseminated to industry stakeholders like maritime engine manufacturers, dynamic pressure and temperature sensor manufacturers, and calibration laboratories. This will be done through trade-journal publications, stakeholder workshops, training, presentations at renowned conferences, and peer-reviewed publications in scientific journals. The consortium will also communicate the goals, research initiatives, benefits, and outcomes from the project to the general society through reports and social media.

Outcomes for the metrology and scientific communities

Through the outcomes from this project, regarding the development of primary calibration standards, national metrology institutes (NMIs) can benefit through knowledge transfer. This will also impact the secondary calibration laboratories and the subsequent calibration chain, up to the end user. The detailed investigations performed on the calibration techniques and sensors will provide a sound basis for good practice guides that are the foundations of standardisation (e.g., OGS against primary reference gas standards; calibrations using impact mass and shock tube methods). Using numerical approaches to understand the influence of dynamic effects during calibration and the investigations on the influence of non-linearities from sensor mountings will provide new insights and guidelines for the metrology and scientific community. The outcomes from modelling approaches to emission predictions and their uncertainty comparison would provide a holistic understanding of the methods and help improve them in subsequent steps.

Outcomes for relevant standards

The outcomes from emission monitoring methods, guides, reports and review of articles along with project progress will be communicated to ISO/TC 158 Analysis of Gases, CEN/TC 264/WG 40, EURAMET TC-MC SCGA – Gas Analysis, and will be harmonised with ISO 8178-1 standard which covers NO_x, PM, N₂O, Particle Number (PN), CO, CH₂O, CH₃OH emission measurements from engines. Guidelines for good practices on pressure calibration and measurement, including the results from inter-laboratory comparison and uncertainty estimation models, will be communicated to the BIPM Consultative Committee for Mass and Related Quantities (CCM) working group on pressure and vacuum (WGPV) and to ISO/TC 108/WG 34/WT 19666, Dynamic Pressure Calibration, to support standardisation work. The consortium participants will also provide regular updates to the EURAMET Technical Committee – Mass and Related Quantities (TC-M) pressure sub-committee. Similarly, the outcomes from the dynamic temperature measurements, guidelines and reports on project progress will be communicated to the Consultive Committee for Thermometry (CCT), CCT Working Group on Contact Thermometry (WG-CTh), and the EURAMET Technical Committee on Thermometry (TC-T). Additionally, the modelling approaches and their uncertainties, the developed mathematical models for uncertainty calculations in dynamic quantities measurements and the numerical approaches to understand different dynamic effects during calibrations will be communicated to EURAMET TC-IM WG M4D. The consortium maintain will open communication with the European Metrology Network (EMN) for Pollution Monitoring (POLMO), EMN for Climate and Ocean Observation (COO), and EMN for Mathematics and Statistics (Mathmet) to provide updates on the project and to receive feedback.

Longer-term economic, social, and environmental impacts

Maritime shipping contributes to transporting approximately 80 % of the trade volume worldwide, and nearly 70 % of the market share on low-to-medium speed engines is from European Union (EU) manufacturers. This is only the engine manufacturing market; the EU is also home to many manufacturers of engine sub-systems. Moreover, according to the European Community Shipowners' Association report, the EU shipping industry directly contributed 54 billion € to the Gross Domestic Product (GDP) in 2018. According to the report, for every 1 € the EU shipping industry contributes to the GDP, a further 1.8 € is supported elsewhere in the EU economy. Similarly, 1.9 jobs are supported elsewhere in the EU economy for every job employed directly by the shipping industry. As the need to reduce emissions grows, and policies worldwide change to support the use of future fuels, the maritime industry should be able to increase its foothold in the global market. With the help of supporting infrastructures and measurement capabilities, the market will refrain from shifting to other

geographies, leading to increased revenue and job growth in the EU. For example, an increase in market share of 5 % in the low to medium engine segment will equal sales by 100 M€, where the market is 2 B€ per year.

The reduction of emissions from the maritime sector is the goal to fulfil societal needs. The development of accurate tools and the proper infrastructure to support new products will increase the system's efficiency and allow the industry to quickly adapt to sustainable choices, lowering the carbon footprint in the sector and dependent industries. This will lead to a cleaner environment with lower emissions, reducing the health risks associated with pollution and decreasing the strain on the medical infrastructure and society. A better standard of living and a healthier society would participate more actively in the economy and, in so doing, add more benefits to the entire cycle.

List of publications

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Project start date and duration:		1 September 2024, 36 months
Coordinator: Dr.-Ing. Ajoy Ramalingam, PTB Tel: +495315923145 E-mail: ajoy.ramalingam@ptb.de		
Project website address: -		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	9. DTI, Denmark	-
2. CMI, Czechia	10. DTU, Denmark	
3. DFM, Denmark	11. FORCE, Denmark	
4. ENSAM, France	12. GERG, Belgium	
5. RISE, Sweden	13. Instrumatic, Denmark	
6. TUBITAK, Türkiye	14. LEC, Austria	
7. VSL, Netherlands	15. TUBS, Germany	
8. VTT, Finland	16. Wärtsilä, Finland	
Affiliated Entities: 17. AMVALOR, France (affiliated to ENSAM)		



Publishable Summary for 23IND10 OnMicro

On-wafer microwave metrology for future industrial applications

Overview

This project will strengthen the European semiconductor industry and facilitate the development of next-generation semiconductor technologies for established and emerging applications, e.g., 6G telecommunications, automotive radar sensors, and wearable electronics for healthcare. The project will develop new, accurate and traceable on-wafer measurement techniques for semiconductors. This includes using new quantum sensing concepts, artificial intelligence and new on-wafer techniques for characterising compound transistors operating up to 220 GHz, and novel 2D, thin-film and semiconductor materials. The project aim is to push beyond the uncertainties and traceability of current on-wafer microwave capabilities for millimetre-wave integrated circuits, particularly those based on compound semiconductors.

Need

Semiconductor chips are critical to a wide range of applications, including healthcare, energy, communications and industrial automation. However, there was a chip global shortage during the COVID-19 pandemic, which posed challenges to the supply chain security. To address these issues, the European Commission introduced the European Chips Act. While this act aims to maintain and expand Europe's technological dominance and ensure resilience and sovereignty in the semiconductor industry, the Radio Frequency (RF) industry is expected to introduce new emerging technologies (e.g., 6G telecommunications, quantum computing etc.), bringing additional challenges and requirements.

These technologies rely on planar RF electronic circuits, the development of which is covered by international roadmaps such as:

- 2020 International Roadmap for Devices and Systems™ (IRDS, <https://irds.ieee.org>)
- Digital Agenda for Europe (<https://www.europarl.europa.eu/factsheets/en/sheet/64/digital-agenda-for-europe>)

After a planar RF circuit is fabricated, its RF performance needs to be measured for quality insurance or during product development as feedback to the design process. This project focuses on improving and developing new on-wafer measurement techniques for the characterisation of RF electronic products to meet the needs of emerging technologies.

By improving and creating new on-wafer measurement techniques, the project will enable the development of advanced medical technologies, e.g., wearable electronics, which require precise on-wafer measurement techniques.

This project positively impacts manufacturing processes of RF electronic devices, as the improved measurement capabilities for semiconductor devices will lead to higher yields, better process control and reduced material waste by less trial-and-error approaches and increased lifetime of the RF products. By promoting sustainable manufacturing processes, the project will contribute to environmental protection.

The advancements achieved through this project will benefit the RF industry and end-users by providing improved measurement capabilities and good practice guides. This project will thus contribute to European competitiveness and help to establish a resilient, secure, and sustainable supply chain for the semiconductor industry.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: July 2024



Objectives

The overall objective of the project is to establish metrological traceability of millimetre-wave and terahertz planar devices for semiconductor technologies by developing new accurate and traceable on-wafer measurements.

The specific technical objectives of the project are:

1. To develop new hardware and software solutions for on-wafer measurements at millimetre-wave and terahertz frequencies by comparing conventional on-wafer measurement systems with new broadband single-sweep systems. In addition to investigate new on-wafer measurement methods (e.g., Rydberg-atom-based probes, artificial intelligence or machine learning driven probing) as alternatives to traditional on-wafer probing methods.
2. To design, manufacture and characterise improved calibration substrates for industrial semiconductor technologies such as BiCMOS (Bipolar complementary metal-oxide-semiconductor) or GaN (Gallium Nitride) up to at least 110 GHz. This includes developing good practice guides and verification techniques to ensure the metrological traceability of the calibration substrates.
3. To develop reliable and accurate on-wafer characterisation techniques for downscaled millimetre wave and terahertz transistors (i.e., up to 220 GHz). In addition, to develop verification techniques and determine reliable uncertainties for on-wafer measurements of millimetre-wave and sub-terahertz (0.1 to 0.3 THz) transistors. This includes an evaluation of the small signal characteristics of advanced transistor technologies, e.g., Indium Phosphide (InP) heterojunction bipolar transistors (HBTs), in order to build equivalent circuit models for high frequency InP transistors and to extract figures of merit (FoM).
4. To develop accurate methods for the characterisation of semiconductor materials, thin-films and novel 2D materials for emerging applications and in addition, to develop new on-wafer-based material characterisation methods and compare them with conventional commercially available material characterisation methods.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (research institutes, calibration laboratories), standards developing organisations (e.g., IEEE Microwave Theory and Techniques Standards Committee (MTT SC)) and end-users (e.g., semiconductor and industry sectors).

Progress beyond the state of the art and results

New techniques in on-wafer measurements: Broadband instruments, Rydberg atoms and AI/ML probing (objective 1)

In previous projects (JRP 14IND02 PlanarCal, JRP 18SIB09 TEMMT), banded on-wafer measurement capabilities up to at least 330 GHz have been installed at European NMIs. However, many challenges such as band-to-band data discontinuities, high resource requirement for the enormous time and resources required to reconfigure the system reconfiguration, the high risk of damage to expensive components and accessories have been associated with these systems. In recent years, new single-sweep systems for on-wafer measurements have been introduced. However, there is no traceability for these systems. Further research into these new hardware solutions is important for all end-users. In addition, new measurement methods have recently emerged e.g., Rydberg atom-based probes, artificial intelligence or machine learning driven probing. Rydberg atoms are a quantum technology that could provide direct on-wafer traceability.

Currently Rydberg atoms are mainly used to measure electric field strength. In this project the technique is used to measure contactless S-parameters on a wafer, which is a route to unprecedented accuracy in S-parameters at very high operating frequencies. The same goal is pursued by using artificial intelligence and machine learning. These techniques are currently used mainly in an automation context but could play an important role in improving probing accuracy at high frequencies.



Metrological traceability for industrial semiconductor technologies (objective 2)

Currently, traceable on-wafer metrology has been successfully established for planar transmission lines, particularly CPWs, on conventional substrate materials. However, there is a lack of traceable metrology for industrial semiconductor technologies.

Significant progress has been made in extending traceability for on-wafer measurements to 330 GHz. However, many applications use specialised semiconductor technologies such as BiCMOS (Bipolar complementary metal-oxide-semiconductor) or GaN (Gallium Nitride) for which design guidelines, traceability and verification do not exist. Due to the complexity of these industrial technologies, current methods developed in previous projects (e.g., JRP 14IND02 PlanarCal and JRP 18SIB09 TEMMT) cannot be used.

This project will fill this gap by developing new traceable methods, good practice guides and verification techniques for BiCMOS and GaN technologies up to at least 110 GHz.

Reliable and accurate on-wafer characterisation techniques for downscaled millimetre-wave and terahertz transistors (objective 3)

Transistors are key components of any integrated circuit (IC). So far, progress towards on-wafer traceability has been demonstrated only for passive devices up to 330 GHz (in JRP 18SIB09 TEMMT). However, active devices, such as transistors, are the basic components of ICs and therefore the development of traceability for these devices is crucial.

The project will achieve transistor characterisation up to 220 GHz for small signal characteristics. Equivalent circuit models for transistor technologies will be generated to allow the extraction of transistor figures of merit, e.g., the transit and maximum oscillation frequency. This will enable traceable methods for on-wafer characterisation of active devices.

Characterisation of semiconductor materials, thin-films and novel 2D materials

The related activities in the JRP 18SIB09 TEMMT project focused on investigating measurements of conventional materials. There are many material characterisation techniques, however, most of these techniques are mainly suitable for measurement of dielectric slabs. New calibration and/or permittivity extraction techniques need to be developed for measurement of thin-film 2D materials and semiconductor materials. Three mainstream methods based on Vector Network Analyzers (VNAs) will be investigated and compared to establish likely accuracy of measurements of these materials up to 500 GHz.

Outcomes and impact

Outcomes for industrial and other user communities

This project will establish new measurement techniques that will directly benefit the European semiconductor industry, ensuring resilience and sovereignty. The application of AI to on-wafer probing is already used in industry and this project will enable industry to use this technique with stated uncertainties, making it usable for quality assurance. Uncertainties for passive and active devices will be established and made available to semiconductor industry. This will enable optimisation of their products, leading to improved functionality and reduced power consumption. It also provides European industry with a competitive edge in the global marketplace and offers cutting-edge solutions meeting the needs of industries.

The results of this project, including best practice guides (e.g., “Recommendations for reliable and accurate on-wafer characterisation techniques for downscaled millimetre-wave and terahertz transistors”) and measurement comparisons, will be widely disseminated to stakeholders including chip foundries, equipment manufacturers, non-European NMI, and the automotive industry. This will be achieved through activities such as organising workshops, presenting project results at major international conferences, publishing in scientific journals and conducting training workshops and on-wafer forums.

A Technical Advisory Group consisting of academic and industrial stakeholders, will be formed and will meet regularly to exchange information with the consortium and to ensure that the project delivers relevant results and information to end-users. Dissemination activities will ensure that the valuable knowledge generated by the project reaches the appropriate audience and contributes to the advancement of the field.



Outcomes for the metrology and scientific communities

Rydberg atom-based on-wafer probing would be a disruptive technology for on-wafer probing due to its non-contact techniques, high bandwidth (1 THz), intrinsic calibration and applicability to large numbers of device under tests (DUT). This project will provide a first insight into how these promises can be realised and will be a starting point for further exploration/industrialisation.

This project will develop new metrological traceability methods and services for industrial semiconductor devices and materials. The results of this project are expected to have a significant impact on the metrology community, leading to the creation of new CMC entries for new broadband and banded on-wafer systems, applied to active and passive devices in different technologies such as BiCMOS, GaN and InP and material characterisation of semiconductors.

The Radio Frequency (RF) industry and semiconductor chip manufacturers will use these calibration services to ensure the quality and accuracy of their semiconductor chips.

The project will transfer knowledge from experienced National Metrology Institutes (NMIs) (i.e., METAS, LNE, NPL, PTB and VSL) to less experienced NMIs (CMI, GUM, and others) on the use of new types of measurement instrumentation. This knowledge transfer will be highly beneficial in enhancing the capabilities of these NMIs and ensuring their competence in on-wafer metrology and materials characterisation. On a larger scale, the project will foster collaboration between European NMIs, thus increasing competitiveness and harmonisation in this field.

In addition, the project will develop new methods for material characterisation of semiconductors from 50 GHz to 500 GHz. Efforts will be made on advancing calibration and data extraction techniques for three main measurement methods including guided free-space, resonators, and on-wafer. A comprehensive report will be compiled, detailing various systems, their operating conditions, recommended procedures, uncertainties, and best practices. This guide will be submitted to EURAMET and made accessible to end-users, ensuring widespread availability of this valuable information. New measurement service is also expected to be launched based on the output from this project.

Outcomes for relevant standards

The outcomes of this project will be integrated into international (IEEE) standards, including P2822 – “Recommended Practice for Microwave, Millimeter-wave, and THz On-Wafer Calibrations, De-Embedding, and Measurements”. The IEEE P2822 standard provides best practice guides and methodologies of on-wafer measurements to the industry.

By incorporating the results of this project into these standards, new and improved measurement methods will be widely disseminated. This will ensure the reliability of measurements for different end-users.

Furthermore, representatives in the project consortium who are involved in international metrological activities will make substantial contributions to the following international activities: BIPM Key Comparison Database, BIPM database of CMC and EURAMET guidance documents such as “Guidelines for the design of calibration substrates and verification structures for industrial applications” and “State-of-the-art in measurements of semiconductor materials, thin-films, and novel 2D materials, for emerging applications”.

Longer-term economic, social and environmental impacts

The improved measurement capabilities for the characterisation of RF electronic products resulting from this project will significantly enhance the competitiveness of European industry in the global market. The exploitation of the results of this project will lead to significant growth of the semiconductor industry in Europe. This will be driven by increased investment from global foundries and increased research activities to support innovation in Europe.

As a result, the European industry will witness the development of advanced technologies and products. This will not only strengthen the position of the industry, but also create new employment opportunities and contribute to improved employment rates and economic prosperity for individuals, and thus to overall economic growth in Europe.

The results of this project and economic growth in Europe will have a long-term impact on end-users who will benefit from improved communication devices, health technologies, transport systems, renewable energy solutions and more. The results of the project will help to improve the quality of life for everyone in Europe.



The improved measurement capabilities for semiconductors resulting from this project will lead to improved yields, reduced material waste and the adoption of sustainable manufacturing practices in semiconductor foundries. By promoting efficient and reliable manufacturing processes, the project will contribute to environmental protection. These benefits will contribute to a more sustainable future for Europe.

Overall, the project will bring economic benefits by stimulating growth and creating employment opportunities. It will bring technological advances that will significantly improve the quality of life for individuals. The project will also have a very positive environmental impact by promoting energy efficiency and resource conservation.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 st June 2024, 36 months
Coordinator: Gia Ngoc Phung, PTB Tel: +49 531 592 2226		E-mail: gia.phung@ptb.de
Project website address: https://www.ptb.de/epm2023/onmicro/home		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	6. CNRS, France	8. Anritsu AU, Austria
2. CMI, Czechia	7. FBH, Germany	9. FormFactor, Germany
3. GUM, Poland		10. Keysight BE, Belgium
4. LNE, France		11. STM Crolles, France
5. VSL, Netherlands		12. ULILLE, France
Associated Partners:		
13. METAS, Switzerland		
14. MPI, Taiwan		
15. NPL, United Kingdom		
16. UNIBAS, Switzerland		
17. UoM, United Kingdom		
Affiliated Entities: 12. ULILLE, France affiliated Entity linked to no.6 CNRS		

Publishable Summary for 23IND11 ThermoSI

Thermometry with embedded SI traceability for industrial applications

Overview

Most industrial processes rely on temperature measurement, which directly influences product quality, energy efficiency, and emissions. All conventional temperature sensors exhibit calibration drift leading to inefficiencies. Poor surface thermometry causes process control problems in advanced manufacturing. Poor gas thermometry causes sub-optimal noxious emissions and reduced efficiency. This project will overcome specific process control challenges by implementing embedded traceable thermometry *in-situ* through driftless practical primary thermometry and self-validation, gas/combustion thermometry, and new traceable surface temperature measurement methods. Traceability will be either directly to the redefined SI kelvin, or indirectly via the International Temperature Scale of 1990 (ITS-90).

Need

Advanced manufacturing is considered by the EU to be at the heart of its industrial strategy (E. Westkämper: Towards the Re-Industrialization of Europe - A Concept for Manufacturing for 2030, Springer-Verlag 2014) and new techniques are important for European growth and sustainability (EC COM(2017) 479). Adoption of advanced manufacturing technologies (EC COM(2014) 14), as well as improved energy efficiency (the price differential between Europe and other regions is increasing) and measurement traceability, is key to achieving that. Maintaining leadership in energy efficiency is crucial in a time of growing competition for resources.

The need for improved in-process temperature measurement is demonstrated by a) industries, being Funded or Unfunded Beneficiaries or Associated Partners, identifying their key issues, and b) the requirement to address temperature sensor calibration drift and surface temperature measurement, which were identified as key needs for Advanced Manufacturing in the Draft Strategic Research Agenda published by the European Metrology Network (EMN) for Advanced Manufacturing.

Reliable, traceable surface temperature measurement with thermal imaging is notoriously difficult. It requires knowledge of the surface emissivity and any reflected thermal radiation, including knowledge of the geometry of the scene. Contact probes are even more challenging. There is a need for a completely new approach which can provide a reliable, non-perturbative measurement of the surface temperature in the field of view.

Long-term reliable temperature measurement and control is required to make autonomous production/Industry 4.0 a reality. However, in the harsh measurement environments encountered in industry (e.g. high temperature), sensor materials degrade, and they drift out of calibration. There is a need for practical primary thermometers that measure thermodynamic temperature irrespective of any damage to the sensor.

Traditional techniques for surface temperature measurement such as thermal imaging are seriously compromised due to the unknown emissivity of the surface and reflected and background thermal radiation. For welding, forming, forging and additive manufacturing, surface temperature measurement is not sufficiently accurate. Phosphor thermometry offers a solution but robust coatings, new phosphor formulations and higher temperature operation (up to 1250 °C) are needed.

Self-validating thermometers which make use of an *in-situ* reference temperature are of growing interest for autonomous in-process recalibration but require manual intervention; automation requires recognition of

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PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: September 2024

characteristic features in temperature-time data which is beyond conventional software techniques, and artificial intelligence (AI) solutions are needed. Spectroscopic infrared gas thermometry for industrial hot gas (e.g. combustion) processes also relies on AI to retrieve the temperature, but this needs improvement to reduce the temperature measurement uncertainty to $\pm 2\%$.

These all reflect the need to introduce traceability to the SI in process.

Objectives

The overall aim of the project is to enhance advanced manufacturing processes by improving temperature measurement and control capability. The specific objectives of the project are:

1. To develop techniques for truly traceable, quantitative thermal imaging, by using at least 4 key engineering materials and selected thermographic phosphors with known temperature in the field of view of the thermal imager in the range of $-100\text{ }^{\circ}\text{C}$ to $500\text{ }^{\circ}\text{C}$ with an uncertainty of less than $5\text{ }^{\circ}\text{C}$. This will include characterisation (e.g., spectral, angular, and hemispherical emissivity) of the surface or of the phosphor itself and *in-situ* correction for camera non-uniformity.
2. To improve practical Johnson noise thermometry with a technology readiness level (TRL) of 6, and an uncertainty of less than $3\text{ }^{\circ}\text{C}$, and to provide truly driftless thermometry for harsh environments (e.g., nuclear power generation and decommissioning). In particular, to develop a robust probe assembly for measuring Johnson noise and demonstrate its performance in harsh environments (e.g., high temperatures up to $1200\text{ }^{\circ}\text{C}$, ionising radiation (gamma rays and neutrons), electromagnetic fields).
3. To develop robust thermographic phosphor techniques for surface temperature measurement with an uncertainty of less than $3\text{ }^{\circ}\text{C}$ and up to temperatures of $1250\text{ }^{\circ}\text{C}$ in collaboration with metals processing organisations and end-users (e.g., marine manufacturing), to progress towards the goal of zero carbon production in e.g., steel processing, and more generally improved energy efficiency of heavy industry.
4. To develop artificial intelligence (e.g., machine learning) approaches to enable traceable *in-situ* temperature measurement for industrial applications with an uncertainty less than 2% up to $1500\text{ }^{\circ}\text{C}$, demonstrated through at least three case studies (e.g., i) machine learning for autonomous operation of self-validating thermometers, ii) spectroscopic infrared thermometry for in-situ gas temperature and gas temperature profile measurements and iii) reference surface temperature calibration insert).
5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g., sensor manufacturers), standards developing organisations (e.g., IEC) and end users (metals processing organisations, nuclear power industry, space industry, etc) and via the EMN for Advanced Manufacturing.

Progress beyond the state of the art and results

Significant progress in this collaborative research was made in the two EMPIR projects 14IND04 EMPRESS and 17IND04 EMPRESS 2, particularly in developing working prototypes of several novel thermometers including the phosphor thermometer, self-validating thermocouples, a portable standard flame, and combustion temperature diagnostic techniques.

Thermal imaging (objective 1)

Reliable, traceable surface temperature measurement is notoriously difficult. Currently industry uses contact surface probes which are prone to very large uncertainties (difficult to mitigate or quantify), or thermal imaging which requires knowledge of the surface emissivity and any reflected thermal radiation, including knowledge of the geometry of the scene, to give meaningful temperature measurements. This objective focuses on enabling quantitative thermal imaging via deployment of known temperature artefacts based on thermographic phosphors in the field of view.

Johnson noise thermometry (objective 2)

A practical primary thermometer measures a property (e.g., speed of sound in a gas, or Johnson noise voltage) which can be related to the sensor temperature without the need for calibration, and in some cases e.g., Johnson noise thermometry, all the sensor properties that change in harsh environments can be measured, ensuring the temperature is always determined absolutely. Practical Johnson noise thermometer prototypes work in benign environments but need developing for harsh environments; here the aim is to make

robust practical primary thermometers, using graphene and other constructions, within the time frame of the project and this represents a disruptive development in industrial thermometry.

Phosphor thermometry to 1250 °C (objective 3)

Phosphor thermometry can be used for monitoring the surface temperature of parts undergoing forming, forging, welding or heat treatment but it is only reliable to 750 °C with intermittent use to 1000 °C. The consortium participants, bringing complementary expertise, will go beyond the state of the art by enabling development and validation of phosphor thermometry techniques and instruments up to 1250 °C. This will be through development of robust coating methods and phosphor formulations that exhibit sufficient fluorescence at elevated temperatures, and through in-process implementation in a range of manufacturing field trials. The techniques developed will also be applied to practical devices for calibrating end-user thermometers.

Artificial intelligence (objective 4)

Locating any instance of the melting plateau of self-validating thermocouples and performing the corresponding *in-situ* recalibration is currently a manual operation which limits uptake. New machine learning (ML) techniques will be used to automate this, enabling truly driftless thermometry. *In-situ* measurements of gas temperature at Selective Non-Catalytic Reduction (SNCR) locations at power plants or waste incinerators are essential for efficient NO_x removal from the flue gas (so-called NO_x reduction) and efficient reagent (ammonia, urea) consumption but are too slow and not suitable for real-time process control. Gas temperature profile retrievals with the use of new AI tools will enable real-time temperature measurements, process optimisation and pollutant emission control. For surface thermometry neural net-based dry-block calibrator inserts to provide a practical reference surface temperature will be developed; the AI approach will enable reliable determination of the true reference surface temperature by 3D interpolation of a small network of thermometers.

Outcomes and impact

The project is industry-focused with the outputs being trialled in-process during the project's lifetime. Knowledge transfer will be maximised through holding industry focused workshops; a project newsletter sent to the project's Stakeholder Community; reporting the project's aims, objectives and outcomes in relevant trade journals and at scientific conferences.

Outcomes for industrial and other user communities

The project will establish new resources for enabling traceable, quantitative thermal imaging and phosphor thermometry, practical Johnson noise thermometers which do not suffer from calibration drift, and machine learning techniques for a number of commonly used thermometry scenarios. The direct impact on the industrial project participants is very significant. The introduction of *in situ* traceability to the SI is embedded in all tasks of the project. A stakeholder community will be established, and a workshop will be held in the second half of the project to disseminate outputs, as well as attendance at conferences and publication in scientific and trade journals. More widely, improved temperature measurement will result in tighter process control which in turn enhances competitiveness. Examples of wider uses include the petrochemical industry, nuclear power industry (especially decommissioning which currently requires widespread process improvements, and small modular reactors), shipbuilding, aerospace and space, iron and steel manufacture, oil and gas, automotive industry, consumer electronics industry, metals industries, refractory insulation manufacture, solar heat capture and heat storage, and district heating/cooling networks.

Outcomes for the metrology and scientific communities

The development of the practical Johnson noise thermometer (JNT) is directly aligned with the *mise en pratique* for the redefined kelvin (*MeP-K*) which details how to attain temperature traceability by means of primary thermometry without recourse to any defined scale, and supports the long-term aim of the BIPM Consultative Committee for Thermometry (CCT) (as expressed in the CCT strategy 2021-2030+) to shift emphasis from secondary thermometry (i.e. thermometers that need calibration) to primary thermometry (direct temperature measurement). The route to market for JNTs is built into the project.

The consortium is involved in coordinating the Guides on Thermometry, and several Task and Working Groups, of the BIPM Consultative Committee for Thermometry (CCT). These are responsible for promoting good thermometry practice and traceability to the SI. The consortium also has representation on the EURAMET Technical Committee on Thermometry (TC-T) and will ensure that project outputs are widely disseminated via the EURAMET TC-T activities. In addition, a member of the consortium (NPL) is the past

president of the UK Institute of Measurement and Control (InstMC) and will use the InstMC network to disseminate project outputs to a highly relevant user community.

Outcomes for relevant standards

This project will have a significant impact by enabling industries to ensure a greater level of compliance with relevant standards. This will be achieved through influencing committees including IEC TC 65/SC 65B/WG5 (thermocouple standards e.g., IEC 60584); CCT (wide ranging relevant areas of interest); EURAMET TC-T (wide ranging relevant areas of interest); InstMC – Standards Policy Panel (promotion of excellence in instrumentation and control); IoP ISAT committee (promotion of new developments in sensing).

Better surface thermometry will enhance participants' ability to meet the requirements of standards associated with pre- and post-welding heat treatment temperature, namely BS EN 13445, ASME VIII, PD 5500, and compliance with the umbrella standard ISO 15614-1. Surface coating of marine and aerospace structures is subject to comparable thermometry challenges; here the ability to meeting BS EN ISO 8502-4:2000 will be enhanced. Compliance with the aerospace heat treatment standard AMS2750F will be facilitated by improved low drift temperature sensors such as JNT and self-validating thermometers and the associated SAE committee will be kept informed of the project progress.

As JNT becomes more widespread, industry will look to the European metrology community for guidance on the associated calibration and traceability framework, and standardisation will come to the fore. This project will provide the underpinning work for this. This framework may look significantly different from one designed for conventional thermometers (i.e., the ITS-90). The work will feed into ongoing discussions within the CCT.

Longer-term economic, social and environmental impacts

This project will coordinate expertise distributed across a number of NMIs and enterprises to solve specific measurement challenges. Europe has a very strong high value / advanced manufacturing base when seen in a global context. Its aerospace and space industry supply chains extend throughout Europe and are largely knowledge-based. Enhancement of efficiency in processes will breed innovation and technological solutions, with a resulting improvement in the competitiveness of industry across the EU. This in turn boosts economic output and growth and both retain and create high quality jobs in several sectors.

Industry accounts for almost a quarter of energy consumed within the EU, with power generation, manufacturing and industrial processing accounting for two thirds of greenhouse gas emissions. Improving the reliability of thermometry, which is the basis of much process control in industry, is a key enabler to improving energy efficiency. Expertise in energy efficient processes is identified by the EC as being very likely to be a growth area in the near future and this will give a competitive edge to European industries.

In nuclear decommissioning, the requirement for traceable low uncertainty thermometry of nuclear waste storage containers over the timescale of tens to hundreds of years or more is required until waste is secured in planned underground storage repositories. The measurement of temperature is a key assurance monitoring parameter for such containers, so a process ready JNT and quantitative thermal imaging and phosphor thermometry are key enablers.

The EU also has a vibrant sensor manufacturing base; the global market for temperature sensing alone is estimated to be worth €4.5 billion and sensors for monitoring process variables account for the majority of this. EU sensor manufacturers can take advantage of the project developments through licensing and selling innovative and improved sensors in the global market. Most of these manufacturers are small- to medium-sized enterprises. AI/ML and hardware developments are expected to lead to post-project spin-off activities e.g., industrial commercial instrument development.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 September 2024, 36 months
Coordinator: Henrik Kjeldsen, DTI		Tel: +45 7220 2909
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. DTI, Denmark	7. DTU, Denmark	10. Beamex, Finland
2. CMI, Czechia	8. NSC-IM, Ukraine	
3. PTB, Germany	9. OVGU, Germany	
4. SMU, Slovakia		
5. UL, Slovenia		
6. VTT, Finland		
Associated Partners:		
11. BAE, United Kingdom		
12. CCPI, United Kingdom		
13. Metrosol, United Kingdom		
14. NPL, United Kingdom		
15. STRATH, United Kingdom		
16. UoM, United Kingdom		



Publishable Summary for 23IND12 ADAM

Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing

Overview

Advanced manufacturing enables novel design and production techniques for industrial products with complex freeform geometries. It also meets the increasing demand for fast and contactless measurements in industrial quality control using optical sensors. However, current simulation-based methods using Digital-Metrological Twins (D-MTs) to determine measurement uncertainty do not cover such developments in advanced manufacturing. To address this issue, this project will develop reliable model descriptions, accurate mathematical models for use in D-MTs, traceable parametrisation methods for measurement uncertainty evaluation in D-MTs. The project will also optimise the performance of the developed D-MTs for advanced manufacturing applications, as well as producing case studies comparing optical and tactile measurements using complex freeform geometries and guidance for D-MT use in advanced industrial applications.

Need

Advanced manufacturing, and hence industrial metrology, are consistently evolving. However, such developments produce demands for new and improved technology, assembly concepts and designs, more accurate measurement methods and improved quality assessments of freeform geometries. Thus, better knowledge of measurement uncertainties is vital for the evaluation of product quality and for time and cost savings in advanced manufacturing.

The need for time efficiency in industrial metrology supports the use of simulation-based uncertainty evaluation (e.g. D-MTs). Indeed, D-MTs play an important role in measurement uncertainty determination in industry. However, currently D-MTs are only available for a limited number of measurement tasks and do not cover the full spectrum of part geometries demanded by users of coordinate measuring machines (CMMs) and machine tools (MTs) in advanced manufacturing.

In addition, the proper use of D-MTs in industrial metrology also depends on the quality of the D-MT results, which are dependent on (i) the quality of the models available (i.e. the description of the measurement device, the measurement process, the specimen under test and their mutual interaction), and (ii) the parametrisation of the model (crucial for the traceability and reliability of the measurement results). Therefore, methods for high quality D-MTs with robust parameterisation need to be developed.

Recent developments in sensors and sensor systems in industrial quality control have enabled the substitution of classical tactile CMMs with more versatile multi-sensor CMMs with different, interchangeable sensors. Similar developments have also been observed for MTs. In particular, the use of optical sensors has increased in popularity as they can be used to capture large areas of a parts' surface in a fast and cost-efficient manner, and they are suitable for measurements of delicate parts that cannot be probed tactilely. However, current D-MTs for CMMs or MTs are predominantly limited to tactile probing. Therefore, the rapidly growing number

Report Status:
PU – Public, fully open

Publishable Summary

Issued: August 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



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of machines that use contactless (optical) sensors lack models (e.g. D-MTs) that cover the numerous error sources typical to these systems.

Objectives

The overall goal of the project is to provide methods and tools in metrology for advanced manufacturing processes to suit the needs arising from a paradigm shift in part properties and measurement techniques. In particular, mathematical descriptions will be developed for optical sensor technologies and freeform-shaped workpieces that take into account the relevant uncertainty contributions. The mathematical models will be usable for D-MTs and represent measurement processes, CMMs, MTs, and workpieces in industrial applications.

The specific objectives are:

1. To determine the measurement uncertainty sources attributed to **freeform geometries**, and to develop accurate mathematical models for use in D-MTs. This includes the (i) evaluation of the D-MTs, (ii) the experimental comparison of the deviations of freeform geometries to prismatic standards, and (iii) the creation of virtual reference artefacts for representative freeform standards.
2. To evaluate the behaviour and inherent properties of at least 3 different types of **optical sensors** integrated in CMMs and/or MTs. This includes the determination of the influence of (i) surface characteristics, (ii) surface tilt and (iii) curvature on the interaction between the optical sensors for freeform and prismatic geometries, as well as the development of reliable mathematical models for D-MTs.
3. To develop methods for the **traceable parameterisation of models** used for measurement uncertainty evaluation in D-MTs. This includes the identification of suitable measurement standards and procedures for the parameterisation of D-MTs and the development of parameterisation strategies for (i) freeform geometry measurements and (ii) for optical sensor measurements.
4. Using the D-MTs developed in Objectives 1-3, to optimise their performance for economically efficient application in advanced manufacturing. This will include **case studies** comparing optical and tactile measurements using freeform geometries and prismatic parts in order to (i) verify D-MT application and (ii) to produce good practice guidelines for D-MT use.
5. To **facilitate the take up of the technology and measurement infrastructure** developed in the project by the EMN Advanced Manufacturing, the measurement supply chain, standards developing organisations (e.g. ISO, VDI/VDE-GMA), and end users (e.g. automotive, machine industry, micromanufacturing, renewable energy and medical sectors).

Progress beyond the state of the art and results

This project will build upon the results of previous projects 17NRM03 EUCoM, 19ENG07 Met4Wind and 20IND07 TracOptic. In 17NRM03 EUCoM, the uncertainty determination through comparison measurements was investigated for tactile measurement of selected prismatic and freeform geometries, however optical sensors and D-MTs were not considered. Through investigations of optical measurements of blades, 19ENG07 Met4Wind focussed on metrology for wind energy systems, but neither a range of optical sensors, nor other freeform geometries were within its scope. In 20IND07 TracOptic, physical models of selected sensors were developed, but data-driven models were not considered.

Mathematical models for measurement uncertainty determination of freeform geometries by D-MTs

D-MTs and numerical simulations play an important role in measurement uncertainty determination in industry, however the currently available methods do not cover the full spectrum of part geometries demanded by users of CMMs/MTs in advanced manufacturing. This project will go beyond the current state of the art by developing validated D-MTs that describe freeform geometries, and their measurement. In addition, the project will develop physical and virtual measurement standards to ensure traceable parametrisation for the D-MTs' application. Terminology for freeform measurements will also be established in order to provide consistency across the metrology and scientific communities and standardisation organisations. This project also intends to extend the applicability of D-MTs to measurements of complex freeform geometries across all areas of advanced manufacturing.

Mathematical models for D-MTs of optical sensors integrated into CMMs/MTs

Current D-MTs for CMMs or MTs are predominantly limited to tactile probing. In contrast there is an increasing demand for the use of optical sensors in advanced manufacturing, as these sensors enabling fast capture of high-resolution data and help to expand the range of measurable parts. This project will create validated D-MTs for the uncertainty determination of optical sensors commonly used in coordinate metrology. The results will expand the state of the art to emerging production methods and current industrial demands for solutions to metrological challenges and help to support faster, reliable, and more cost-efficient measurements.

Traceable parametrisation of D-MTs for measurement uncertainty evaluation

Currently, the traceable use of D-MTs to determine measurement uncertainties requires the identification of all significant contributions and the parametrisation of their influence via dedicated measurement routines. Routines and measurement standards already exist for tactile measurements of prismatic parts on CMMs, however few methods are available for MTs. The project will go beyond the current state of the art by developing procedures for the traceable parametrisation of D-MTs for tactile and optical probing of prismatic and freeform geometries on CMMs and MTs. This should then enable their application to a wide range of measurement tasks in advanced manufacturing.

Optimisation and case studies verifying the developed D-MTs

Simulation techniques, such as D-MTs, used for the determination of measurement uncertainties currently require 10^4 to 10^6 iterations and must be accompanied by detailed parametrisation measurements of the D-MTs. In contrast, cost-efficiency demands in industrial applications require a reduction of the number of iterations to only a few hundreds, which creates a significant gap between the requirement for the trustworthy use and the practical application of D-MTs. The project will address this issue by developing good practice guidelines for the cost-efficient, and traceable use of validated D-MTs. The guidelines will be made available to end users and standardisation committees and are intended to support the trustworthiness and sustainable dissemination of D-MT technologies.

Outcomes and impact

Outcomes for industrial and other user communities

This project's development of D-MTs for the measurement uncertainty evaluation of freeform geometries and the use of optical sensors in coordinate metrology should provide industry with improved measurement capabilities for complex geometries and the use of increasingly fast, accurate, reliable, and versatile measurement technology to advanced manufacturing industries.

The project will establish validated D-MT models for tactile and optical measurements of complex freeform geometries and commonly used optical sensors. The project's development of the D-MTs models will greatly extend the range of their application in CMM and MT measurements to cover complex freeform geometries and delicate objects (that require optical probing). The increased measurement capabilities in MTs will also contribute to faster and more cost-efficient production lines in manufacturing industries. The D-MT models are expected to be integrated in CMM software as part of the virtual coordinate measuring machine (VCMM), originally developed by PTB. This D-MT updated VCMM will then be made available to users from advanced manufacturing industries and other communities. To help ensure that the D-MT updated VCMM is suitable for end-users in industry, PTB will work closely with industrial participants Hexagon, Mitutoyo, Zeiss, who have previously been involved in the integration of PTB's VCMM into their own systems. Further to this the project will benefit from input from industrial stakeholders in its stakeholder committee.

Finally, the project will create 2 good practice guidelines for the reliable and trustworthy application of traceable D-MTs for both freeform measurements and optical sensors in advanced metrology applications. The guidelines will be made freely available to end users via the project website and an open access repository. The results of the project will also be provided to the EMN Advanced Manufacturing, so that they can be promoted widely to their stakeholders in the European advanced manufacturing industry.

Outcomes for the metrology and scientific communities

The project will develop a glossary for relevant terminology of freeform geometries and the use of D-MTs for the uncertainty evaluation. The glossary will help to establish consistency across the metrology and scientific communities. The glossary will be disseminated to the metrological and scientific communities together with

the project's good practice guidelines via the project website and an open access repository. This should support an increase in the use and understanding of D-MTs by calibration laboratories and less experienced users in the scientific community.

The project will also develop a new measurement standard (i.e. a freeform artefact design), together with methods and routines for the parametrisation of the D-MTs, which can be used by stakeholders to enable traceable measurements and uncertainty determination. The design of the freeform artefact will be made publicly available in an open access 3D cloud repository, such as "Reality Cloud Studio" such that all users from the scientific community can access it.

During the project, close ties to the EMNs for Advanced Manufacturing and MATHMET will be sought so that the outcome of this project can be used in outlining roadmaps and updating the EMN's existing strategic research agendas documents and consequently stimulating additional related research.

Further to this, the project will engage with the metrology and scientific communities via the publication of joint research papers in high impact peer-reviewed journals, through the presentation of the project at conferences and as part of the knowledge transfer the project will host 3 stakeholder workshops, as well as a special session dedicated to using D-MTs at the "International conference on Digital Twins" 2026.

Outcomes for relevant standards

The project will provide input to several international and national standards bodies and their guidelines dealing with coordinate metrology using CMMs and MTs. These include EURAMET TC-Length, BIPM's Consultative committee for Length (CCL), ISO/TC 213 Dimensional and geometrical product specifications and verification WG 4 Uncertainty of measurement and decision rules, WG 10 Coordinate measuring machines and Advisory Group (AG) 12 Mathematical support group, ISO/TC 39/SC 2 Test conditions for metal cutting machine tools, ISO/IEC JTC 1/SC 41 Internet of things and digital twin and VDI/VDE GMA TC 4.31 Coordinate measuring machines.

Further to this, the project will develop a proposal for the establishment of a working group devoted to the application of D-MTs in advanced manufacturing.

Existing standards for geometric product specification only sparsely cover the use of D-MTs in coordinate metrology. For example, ISO/TS 15530-4 describes the use of numerical simulation for the uncertainty determination in a general manner, while ISO 23247-1 covers Digital Twin (DT) systems in automation and manufacturing and providing definitions for general terminology. The ISO 230 series covers the determination of parameters describing geometric errors of MTs and provides a set of basic equations for the estimation of measurement uncertainty for MTs. The project's glossary for the use of D-MTs in coordinate metrology will provide information for future extensions of the ISO 10360 series and support more consistent terminology for DTs in advanced manufacturing. Furthermore, the project's good practice guidelines for the reliable and trustworthy use of D-MTs in advanced manufacturing will support the extension of standards in the ISO 15530 and ISO 230 series.

Longer-term economic, social and environmental impacts

In the longer-term this project's improved capabilities for the use of D-MTs for the measurement of freeform geometries and the exploitation of optical measuring systems in industrial applications will support future progress in advanced manufacturing, such as fast, versatile, and traceable quality control processes. The developed D-MTs will help to strengthen the European manufacturing industry's ability to innovate products (e.g. novel product designs required for energy-efficient aircraft and electric vehicles), as well as to make manufacturing operations more time, cost and energy efficient (helping with the mitigation of climate change).

The project's guidelines for D-MT use and trustworthiness will help to increase long-term end-user confidence in metrology devices and to support the competitiveness of CMM and MT manufacturers and the spectrum of calibration services offered by laboratories, mainly SMEs. The project will also help MT producers to be able to offer products for fast and flexible on-machine and in-process measurements thus closer to the manufacturing process and reducing waste material and the re-working of workpieces. This will benefit European citizens by supporting employment and ensuring higher quality products.

Finally, the project's outcomes should have a longer-term impact on the provision of new calibration services for CMMs, MTs and optical sensors in. This will support, for example, medical implants, electric mobility applications, and non-contact calibration of femoral implants. Such developments should open up new or enable the extension of existing Calibration and Measurement Capabilities (CMCs) for NMIs/DIs.

Project start date and duration:		01 September 2024, 36 months
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Project website address: https://www.adam.ptb.de		E-mail: daniel.heisselmann@ptb.de
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	8. DTU, Denmark	16. eumetron, Germany
2. CMI, Czechia	9. ENS Paris Saclay, France	17. Hexagon, Germany
3. GUM, Poland	10. IDEKO, Spain	18. Mitutoyo, Germany
4. LNE, France	11. PK, Poland	19. Zeiss, Germany
5. RISE, Sweden	12. POLITO, Italy	
6. VSL, Netherlands	13. RWTH, Germany	
7. VTT, Finland	14. TEKNIKER, Spain	
	15. UNIPD, Italy	
Associated Partners: 20. AIST, Japan		

Publishable Summary for 23IND13 ScreenFood

Metrology for food safety in the circular economy: targeted and screening methods for contaminants in food and recycled packaging

Overview

To ensure a high level of food safety throughout production and distribution, it is crucial to improve and harmonise analytical techniques for contaminant quantification. This constitutes the basis for reliable data regarding food product compliance with regulations and for resolving disputes and minimising financial losses within the food industry. The project will develop reference methods and reference materials for quantifying contaminants in both food and food packaging, with a specific emphasis on recycled materials. These metrological tools will aid industries in guaranteeing the delivery of safe food and sustainable packaging while adhering to regulatory requirements.

Need

Ensuring food safety is of paramount importance, as it involves safeguarding consumers from potential harm caused by food contamination. The focus on safety is a central priority for EU lawmakers. Furthermore, as outlined in the circular economy action plan, the development of a sustainable food system is a critical objective. Industries have a pivotal role to play in achieving this objective by adopting strategies that reduce food waste, minimise environmental impact, and prioritise consumer well-being.

However, progress towards these goals can sometimes face obstacles, including the risk of eroding consumer confidence in food quality. Such challenges can negatively impact the standing of the European food industry in the global market. Factors such as the increased use of recycled and sustainable packaging materials and the growing awareness of emerging contaminants necessitate immediate attention.

End-users of measurements related to contaminants, including analytical laboratories, regulatory authorities, and decision-makers, rely on accurate analytical procedures with traceability to SI units. Consistency and accuracy in assessing and managing contaminants are vital to making informed decisions and maintaining the integrity of the food supply chain. However, meeting these requirements can be challenging. Existing standard procedures may require enhancements, or they may not exist for specific analytes or matrices (or their combinations).

Furthermore, appropriate (Certified) Reference Materials covering contaminants in relevant food and food contact materials are often not available.

Improving and harmonising reliable analytical procedures that provide traceability to SI units are essential actions to address these gaps effectively. Such measurement capabilities must be supported by reference materials that address specific matrix requirements, relevant analytes, and emerging trends in food packaging. Experience has shown that, especially in the case of complex analytical procedures, training laboratory staff in sample preparation, instrumental analyses, and result interpretation is urgently needed alongside harmonised protocols and reference materials to ensure quality control effectively.

Objectives

The overall aim of the project is to develop analytical strategies and reference materials supporting food and food packaging industries in the provision of safe and sustainable products compliant to legislation. The project will establish a metrological network able to provide, in collaboration with research centres and industries, innovative harmonised standards, internationally recognised, aimed at the detection and quantification of contaminants in food, with a focus on those possibly migrated from virgin and recycled food packaging materials.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024

The specific objectives are:

1. To improve protocols for the **quantification of the mineral oil aromatic hydrocarbons (MOAH) fraction** and for the quantification of the fraction consisting of substances with three or more aromatic ring systems (3+MOAH), including sample preparation procedures for food matrices not covered in the development of ISO/DIS 20122. This will include selected food types from the SCoPAFF categories with a fat content between 4 % and 50 % ($\text{MOAH} \leq 1.0 \text{ mg/kg}$) and below 4 % ($\text{MOAH} \leq 0.5 \text{ mg/kg}$). Reliable MOAH quantification shall be demonstrated in presence of biogenic interfering substances.
2. To develop sensitive analytical procedures for detecting and quantifying **per- and polyfluoroalkyl substances (PFAS) in selected matrices**, in line with the requirements of Commission Regulation (EU) 2023/915, meeting the limits of quantification (LOQ) specified in Commission Recommendation (EU) 2022/1431, ranging from $\leq 0.002 \text{ } \mu\text{g/kg}$ to $\leq 0.5 \text{ } \mu\text{g/kg}$ for relevant PFAS groups depending on the matrix. The following PFAS will be addressed: PFOS, PFOA, PFNA e PFHxS, as well as emerging perfluoroalkyl substances (e.g., GenX, ADONA, PAPs, Fluorotelomer alcohols and sulfonates). Food matrices will be selected in order to cover categories that pose different analytical challenges, from (i) water/moisture-content (ii) Fatty and (iii) High protein matrices. Food packaging materials (both virgin and recycled) will be studied as well.
3. To develop **traceable and highly accurate reference materials** for quality control and quality assurance purposes. These materials will be designed for key contaminants like MOSH, MOAH, and PFAS in relevant food and food-related matrices, such as vegetable oil, infant formula, fish, milk, and food packaging.
4. Develop screening methods addressing new/existing organic and inorganic contaminants, in virgin and recycled packaging such as bio-based food contact materials and reusable materials. To detect contaminants' migration in food simulants and selected food matrices as well as to foster the research in the discovery of Emerging and Novel PFAS through non-targeted screening. To implement metrological approaches for the determination of total extractable organic fluorine (EOF) in selected matrices as well as to address direct transportable/portable rapid screening methods for performance and comparison to existing laboratory methods.
5. To **facilitate the take up of the technology and measurement infrastructure** by the supply chain (e.g., regulatory bodies, NMIs, DIs and EMN for Safe and Sustainable Food), standards developing organisations (e.g., CEN, ISO, UNI, IOC, Codex Alimentarius), and end users (e.g., reference laboratories, the food industry), to ensure that the advancements made in the project benefit the wider community.

Progress beyond the state of the art and results

Objective 1: Identification and Quantification of MOSH and MOAH in Food Matrices:

The project will enhance the applicability of the procedure outlined in ISO/DIS 20122. This will involve a thorough revision of the Standard Operating Procedure (SOP) with detailed instructions to eliminate analytical interferences and assess chromatograms. The goal is to harmonise the procedure and enable routine application with quantification limits for MOAH in all food matrices at least as specified by SCoPAFF: 2.0 mg/kg for fats and oils and fatty foods with fat contents above 50 %, 1.0 mg/kg for foods with a fat content between 4 % and 50 % and 0.5 mg/kg for foods with a fat content below 4 %. This will cover food matrices so far not included in validation studies. For the first time, 3+MOAH will explicitly be addressed. Additionally, a video training resource will be developed to facilitate the harmonised integration and interpretation of chromatographic data. GCxGC procedures will be developed and harmonised to identify the patterns of the 3+MOAH fraction. This is expected to significantly improve the identification of toxicological relevant MOAH contamination sources.

Objective 2: Sensitive Analytical Procedures for PFAS Detection and Quantification:

The project will develop reference methods and materials to support industries and regulatory bodies in detecting PFAS in relevant food matrices and food packaging materials. Focus areas include drinking water, milk, fish, and vegetables, which pose analytical challenges. The outcomes are expected to contribute to the evolving regulatory framework concerning PFAS, both within and outside the EU. Various extraction and clean-up methods will be explored to streamline sample preparation while maintaining sensitivity and reproducibility. The project will provide validated analytical methods for relevant matrices, such as drinking water, fish, milk, vegetables, and packaging materials, with limits of quantification ranging from $\leq 0.002 \text{ } \mu\text{g/kg}$ to $\leq 0.500 \text{ } \mu\text{g/kg}$, in line with recent regulations.

Objective 3: Development of Traceable and Accurate Reference Materials:

Reference materials and candidate Certified Reference Materials (CRMs) will be developed for the determination of MOSH/MOAH in food matrices and PFAS in selected food and food packaging matrices. This will support trueness, precision and between-laboratory consistency of measurement results in routine laboratories. For mineral oils, matrix-free reference materials will be created, addressing a current market gap, and will be provided for spiking selected food matrices. The project will also work on efficient and automated clean-up processes to minimise the use of hazardous substances. Novel isotopically labelled compounds will be investigated to enhance the sensitivity and specificity of HPLC-MS-based analytical methods for PFAS quantification in selected matrices.

Objective 4: Development and Validation of Screening Methods for Contaminants in Packaging:

The project will develop validated and, wherever possible, SI-traceable methods to support standardised quantification of organic and inorganic contaminants, including non-polar organics (e.g. hydrocarbons, oligomers), PFAS, total extractable organic fluorine, and metals. New methods will be validated and implemented to reduce measurement uncertainty or support relevant legislation. Screening methods will be devised to address the complexities of monitoring contaminants in recycled and virgin packaging materials, including eco-friendly containers. These methods will be standardised and employed in migration studies. For recycled packaging, they will enable the identification and quantification of chemical contaminants from previous uses, such as ink residues, adhesives, or cleaning agents. In the case of novel/biobased materials, these methods will help detect potential natural chemical compounds that may migrate into food, affecting its quality and safety.

Outcomes and impact

Outcomes for industrial and other user communities

The food industry will gain access to validated measurement methods and reference materials essential for accurately quantifying chemical agents that may unintentionally contaminate food products due to inadvertent or adventitious contamination. Unlike contaminants deliberately added for profit through food adulteration or fraud, accidental contamination typically occurs at extremely low levels, posing a significant challenge for detection. Therefore, determining trace levels of contaminants near the limits of detection necessitates state-of-the-art analytical techniques. The project's outcomes will bolster the food industry's capacity to detect and quantify accidental chemical contaminants in both food and packaging materials, thereby mitigating the risk of product recalls.

Presently, the lack of reference materials for certain contaminant analyses poses a significant challenge, as laboratories must provide quality assurance for compliance or accreditation purposes. Food industry laboratories will be able to employ (Certified) Reference Materials (CRMs) as quality control materials for key contaminants. This will expedite the rapid implementation and maintenance of reliable measurement results.

Specifically addressing Mineral Oil Saturated Hydrocarbons (MOSH) and Mineral Oil Aromatic Hydrocarbons (MOAH), the project will develop a comprehensive video training for the proper application of the complex LC-GC-FID analytical procedure. Additionally, improved methodologies for characterising the MOAH fraction regarding the compounds displaying 3 and more rings (3+MOAH) will be developed, enhancing the capabilities to meet the requirements set by EFSA.

Outcomes for the metrology and scientific communities

The metrology and scientific communities will have the opportunity to participate in international interlaboratory studies, allowing them to benchmark themselves against peers, enhance their abilities to measure certain contaminants more accurately in selected matrices, with lower detection limits.

The project's analytical methods and the results from three interlaboratory comparisons will serve as an unparalleled foundation for metrologically traceable reference materials. Innovative analytical approaches for assessing packaging materials in terms of inorganic and organic contaminants will be disseminated to the metrology and scientific communities through peer-reviewed publications, measurement protocols, and guides. Additionally, reliable data on 3+MOAH, as requested by the European Food Safety Authority (EFSA), will be made available in the near future.

These outcomes will impact on measurement and testing laboratories and academics, enabling them to produce more accurate and reproducible scientific results and assess their applicability to diverse investigative areas. As a result of these interlaboratory comparisons, all uncertainty parameters for method validation and guidance on using uncertainty measurements in conformity checks or legislative compliance will be obtained. These considerations and results will be disseminated through scientific papers and communications at conferences organised for the food chemistry or metrology community.

On a broader scale, the project will fortify collaboration among European National Metrology Institutes (NMIs) in the realm of food safety, enhancing their competence and competitiveness in characterising mineral oils, PFAS, and organic and inorganic contaminants within a competitive international market. The project's outcomes will impact metrology thanks to the strong connections of the consortium with relevant metrology networks, research infrastructures, and confederations, such as the European Metrology Network for Safe and Sustainable Food, METROFOOD RI, and IMEKOFOODS.

Outcomes for relevant standards

The consortium will actively promote the project's results within the standardisation community and contribute inputs to the standardisation process of organisations like ISO, CEN, and UNI. Specifically, standards relevant to the project that are either in preparation or revision will be identified, and efforts to advance these standards will be suggested to the appropriate working groups or committees.

The project's results will serve as a foundation for the development of new international standards and standard operating procedures (SOPs) related to horizontal methods, contaminants, and packaging. This is particularly important for challenging food matrices and infant foods, where special attention is required due to the low body mass during child development.

Furthermore, the project will propose guidelines covering various aspects, such as production, packaging materials, and storage, following the project's conclusions. It will also create a specific protocol for the identification of 3+MOAH.

The validation of existing methods, involving additions or revisions to uncertainty and analytical parameters or application fields, will be a primary focus.

The project's ultimate goal is to submit inputs with innovative significance to existing and new standards promoted by international standardisation bodies, ultimately advancing measurement and testing practices.

Longer-term economic, social, and environmental impacts

Recognising food contamination as a global challenge, the World Health Organization has highlighted its significance in various documents and reports. This project will address the imperative need for monitoring and reducing contaminants in food by developing Certified Reference Materials (CRMs) and validated, harmonised quantitative methods. The resulting safer foods will improve the health status of consumers, reducing social healthcare costs and benefiting citizens worldwide.

Furthermore, the project will offer insights into the sources of contamination for selected contaminants in food. Understanding the factors influencing chemical burden in food will aid in reducing contamination throughout the entire farm-to-fork continuum.

The project's findings on contamination from various types of food packaging will raise awareness and promote the safe use of recycled materials, enhancing the trust of end-users and consumers. Additionally, packaging and environmental associations will derive benefits from the project's outcomes.

In the long term, the project aligns with societal goals by addressing areas for improving the safety of food contact materials and contributing to the circular economy. As a result, the project will enhance knowledge about the potential impact of recyclates used in packaging on the quality and safety of packed food. This is especially relevant as European Union countries are gradually increasing the use of recycled materials in packaging and recycling cycles.

In conclusion, this project's outcomes will have a substantial and positive impact on food safety, measurement accuracy, standardisation, and long-term economic, social, and environmental aspects, aligning with global efforts to ensure the safety and sustainability of the food supply chain. This is aligned with 2030 Agenda for Sustainable Development of United Nations [3], in particular referring to "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" (Objective 2).

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2024, 36 months
Coordinator: Chiara Portesi, INRIM Project website address: -		Tel: +39 011 3919332 E-mail: c.portesi@inrim.it
Internal Beneficiaries: 1. INRIM, Italy 2. BAM, Germany 3. GUM, Poland 4. IMBiH, Bosnia and Herzegovina 5. JSI, Slovenia 6. NIVA, Norway 7. TUBITAK, Türkiye 8. ZRS Koper, Slovenia	External Beneficiaries: 9. Chiron, Norway 10. CVUA FR, Germany 11. DTU, Denmark 12. EUROLAB, Europe 13. IAPR, Greece 14. MRI, Germany 15. Natureef, Poland 16. Sciensano, Belgium 17. UT, Estonia	Unfunded Beneficiaries: 18. AS, Germany 19. GEA, Slovenia 20. Gerstel, Germany 21. JOTIS, Greece 22. KB Folie Polska, Poland 23. Nestlé Waters, France
Associated Partners: 24. KLZH, Switzerland 25. LGC, United Kingdom 26. METAS, Switzerland 27. realcycle, Switzerland 28. SQT, Switzerland.		

Publishable Summary for 23IND14 xDDiff

Multidimensional optical diffusion for the measurement of appearance

Overview

Product appearance and visual branding play important roles in influencing consumer purchase decisions, as they significantly shape perceptions of 'quality' and 'desirability'. However, solutions that enable industry to carry out reliable, stable and traceable measurements of the visual appearance of manufactured objects are still missing. This project aims to address that need by providing tools for carrying out the traceable measurement of the visual appearance of non-isotropic, non-flat and functional surfaces and of translucent materials. It will provide practical solutions for measuring haze, gloss, iridescence, matte and translucency of objects, which will also help to improve the quality of virtual reality rendering models.

Need

In industries dealing with real objects, product appearance and visual branding are important drivers for consumer purchase decisions because they underpin perceptions of 'quality' and 'desirability'. The control of appearance is thus essential for almost all traditional industrial fields (automotive, cosmetics, packaging, textile, paper). In industries involving virtual objects (videogames, metaverse, virtual prototyping, digital twins) and 3D printing, the quality of rendering and its realism are closely linked to the ability to capture and process the appearance of physical objects. This capability must match the performance level of the human visual system and align with the specific scale required for object's display or printing size. In advanced manufacturing industries, it is essential to have precise control over the directional reflectance and transmittance properties of materials to optimise reflection and/or transmission in specific parts of the optical spectrum. Additionally, this allows light to be redirected or guided in relevant directions to enhance the energy efficiency of buildings, greenhouses, light emitting diode (LED) lighting systems and photovoltaic panels.

Bidirectional Reflectance Distribution Function (BRDF) scales maintained by NMIs have been compared and consolidated over the past decade. However, the measurement of the BRDF at a few geometries is not enough to fully characterise the appearance of challenging surfaces and effects (e.g. brushed metals, functional surfaces, anisotropic samples and sparkle). For this, image-based goniospectrophotometers are required. They must be traceable and validated by comparison. Traceable BRDF measurements on non-flat surfaces have never been done even though the need has been expressed by industry for more than a decade. Bidirectional Transmittance Distribution Function (BTDF) and Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF) primary scales were established during EMPIR projects 18SIB03 BxDiff at the NMI level, but the uncertainty of BSSRDF measurements is still very high and must be reduced in order to answer the need of measurement of translucency.

Goniospectrophotometers developed at NMIs are very complex and their measurements very time consuming. To be used in industry, a simplification is required. For this, it is necessary to determine the relevant angular configurations, the sampling step and the sampling strategy according to the type of surface being studied. In colorimetry, there are metrics for comparing colour differences. However, no such metric exists for comparing BRDF measurements. Although progressing, the measurement of the BSSRDF is still not sufficient to simulate the appearance of translucency in rendering models. Moving forward requires the measurement of effective parameters such as scattering and absorption coefficients and the phase function of the material.

Whereas the measurement of gloss has progressed significantly over the last decade, the measurement of mattness is inexistent, even though this visual effect is very much used in industry. Therefore, it is crucial for

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: September 2024

work on the optical and visual characterisation of mattness to start. With regards to translucency, several psychophysical studies have been published in the last few years, but the link between BSSRDF and simplified quantities is still missing.

Objectives

The overall objective of the project is to provide industrial-level tools for capturing, reproducing and monitoring the visual appearance of real or virtual objects. The specific objectives of the project are:

1. To develop and characterise image-based goniospectrophotometers, including simplified versions of these and to use these to perform the traceable measurement of optical properties (e.g., BRDF, BTDF, BSSRDF) of actual manufactured surfaces e.g. anisotropic surfaces, non-flat surfaces, functional surfaces and translucent materials with a target measurement uncertainties below 0.5 % for BRDF and BTDF and around 2 % for BSSRDF for full goniospectrophotometers. The target uncertainties for simplified goniospectrophotometers are below 2 % for BRDF and BTDF and 4 % for BSSRDF.
2. To model complex scattering quantities (e.g., BRDF, BTDF, BSSRDF) of industrial surfaces to define quantifying tools for the digitalisation and reproduction of the appearance of materials, including thresholding, sampling strategy, interpolation models and comparison metrics.
3. To develop measurement scales for translucency and mattness. This includes the definition of physical quantities (e.g., BRDF and BSSRDF) which correlate with the visual sensation and the proposal of protocols for their measurement with a target uncertainty of 5 %.
4. To tackle metrological issues in the field of bidirectional spectrophotometry that limit the knowledge and the uncertainties on spectrophotometric quantities, i.e., sphere-based quantities, transmittance of thick samples, multiscale traceability, effective refractive index, specular gloss index.

To facilitate the take up of the technology and measurement infrastructure developed in the project by the EMN Advanced Manufacturing, measurement supply chain (NMIs, instrument manufacturers), standards developing organisations (ISO, CIE), and end users (e.g., automotive industry, video game developers, healthcare sector, visual arts sector, glass manufacturers).

Progress beyond the state of the art and results

This project follows on from previous projects EMRP project IND52 xDReflect, and EMPIR projects 16NRM08 BiRD, 18SIB03 BxDiff and 20SCP01 Smart PhoRa. The progress beyond the state of the art in relation to those projects is summarised below.

Objective 1: Development and characterisation of image-based goniospectrophotometers and their use in the traceable measurement of optical properties (e.g., BRDF, BTDF, BSSRDF) of actual manufactured surfaces

EMRP project IND52 [xDReflect](#) aimed at establishing primary references for BRDF dedicated to the measurement of appearance at the NMI level. Subsequently, EMPIR project 18SIB03 BxDiff successfully established primary references for BTDF and BSSRDF at the NMI level.

Although Europe has achieved the realisation of BRDF, BTDF and BSSRDF quantities that are traceable to the international system (SI) with the highest level of uncertainty, measuring these quantities at a limited number of geometries is insufficient to fully characterise the appearance of challenging industrial surfaces, such as brushed metals, functional surfaces and anisotropic samples. To address that issue, this project will go beyond the state of the art by developing traceable camera-based goniospectrophotometers at NMIs. This will bridge the gap between commercial devices and reference devices, reducing the calibration uncertainty.

Objective 2: Modelling of complex scattering quantities (e.g. BRDF, BTDF, BSSRDF) of industrial surfaces to define quantifying tools for the digitalisation and reproduction of the appearance of material

To improve our understanding of light-material interactions, simulate materials such as fabric or car paint in virtual prototyping, or manage the workflow of 3D printers, models of BRDF, BTDF and BSSRDF are required. While the field of computer graphics has produced numerous models over the past two decades, those are rarely validated against reliable measurements due to the absence of traceable measurements until now. This project aims to go beyond the state of the art by testing the most recent generation of BRDF/BTDF/BSSRDF models against traceable measurements. This will enable the validation or reconsideration of long-standing

assumptions related to parameters such as the “effective refractive index”, “phase function”, and “scattering and absorption coefficients”.

Objective 3: Development of measurement scales for translucency and mattness

Mattness and translucency are increasingly utilised in different industries e.g. automotive and ceramics. However, while the measurement of glossiness has made substantial progress over the last decade, the linkage between the perceptual qualities of mattness and translucency with BRDF and BSSRDF is still lacking. This project will go beyond the state of the art by developing numerical indicators extracted from BRDF and BSSRDF measurements. These indicators will quantitatively assess the levels of mattness and translucency in accordance with the visual perception of human observer.

Objective 4: Tackling of metrological issues in the field of bidirectional spectrophotometry

Currently, NMIs carry out BRDF measurements on one-square-centimetre surfaces, yet manufacturers often require measurements on much smaller surfaces. This project aims to advance beyond the existing state of the art by extending the traceability of BRDF measurements to sub-millimetre surfaces and making them accessible to industry.

Traditionally, the characterisation of transmittance haze and specular gloss relies on a relative methodology involving integrating spheres. However, direct access to these quantities through BRDF and BTDF measurements with goniospectrophotometers has become feasible. Nevertheless, recent findings suggest that the scales obtained through both methods do not agree as expected. The project intends to go beyond the state of the art by clarifying this discrepancy.

Outcomes and impact

Outcomes for industrial and other user communities

The project will deliver a new generation of goniospectrophotometers traceable to the SI and, in terms of optical design and measurement techniques, much closer to instruments used in industry to control or measure visual appearance. This will lead to reduced uncertainty in the calibration of measurement devices and enhanced control of the appearance of manufactured objects. For industry, this means: i) innovation and creation of new visual effects at the R&D stage, ii) less rejection/waste and improvement of the quality at the production level, and iii) reduction of conflict between suppliers and buyers at the delivery stage.

To promote the uptake of the project outputs by the industrial and other user communities, the consortium will organise workshops targeted at these communities and promote them online, at standardisation meetings and via the stakeholder committee.

Outcomes for the metrology and scientific communities

The development of these new goniospectrophotometers, their validation through intercomparisons, and the development of specific samples to support the quality of these comparisons will allow NMIs to validate their current, including recently developed, realisations of bidirectional spectrophotometric quantities.

Studies comparing measurements performed using integrating spheres with those obtained by integrating the BRDF or BTDF may have a significant impact. Presently, most NMIs rely on integrating spheres for their haze or gloss scales. If it turns out that measurement with goniospectrophotometers yield lower uncertainty, NMIs may consider modifying the traceability of haze and gloss measurements. This could extend to all primary measurements conducted using integrating spheres, including hemispherical reflectance or transmittance.

Finally, this project is committed to progress towards the establishment of a genuine European service for the metrology of appearance, which will include the new possibilities developed during the project for the measurement and characterisation of samples and visual effects.

To promote the uptake of the project outputs by the metrology and scientific communities, the consortium will organise workshops targeted at these communities and promote them online, at standardisation meetings and via the stakeholder committee.

Outcomes for relevant standards

The consortium has strong links with the CIE and will present the work and results of the project to CIE TC1-92, CIE TC2-85, CIE TC2-94, CIE TC2-98, CIE JTC 12 and CIE JTC 17. The consortium will actively strive to ensure incorporation of the outputs of the project into CIE Technical Recommendations, standards or guidelines. Additionally, the coordinating organisation is member of the BIPM CCPR and EURAMET-TC-PR, and the consortium has already established links with ISO/TC 6, SIS/TK 157, DfwG Deutsche farbwissenschaftliche Gesellschaft, DIN-Normenausschuss Farbe (FNF) and APMP-TC-PR.

Longer-term economic, social and environmental impacts

This project will make a significant contribution to improving the competitiveness of European industries by establishing a traceable system for measuring appearance, ensuring stability, interoperability, openness and objectivity.

This project aims to strengthen the competitiveness of the industry, potentially improving sales. While this goal may appear to conflict with the pressing need to reduce production and consumption for the preservation of our planet, improved control of appearance leads to better quality control, resulting in reduced waste. Additionally, enhanced rendering models promote more digital prototyping, potentially reducing the number of physical objects produced and distributed. The optimisation of sampling techniques results in reduced data generation and, consequently, decreased digital storage requirements.

Furthermore, the development of functional surfaces that can redirect or guide transmitted light in specific directions contributes to the enhanced energy efficiency of buildings, greenhouses, LED lighting systems, and photovoltaic panels. By enabling better characterisation of the reflective and transmissive properties of functional surfaces, the work carried out in this project will help to improve the performance of these surfaces and thus increase their efficiency.

The social impact of this project will be closely tied to the economic impact discussed above. Better control of appearance will lead to high customer satisfaction, and the improved capture of the appearance of objects will enable their digitalisation and the creation of digital twins of our cultural heritage so that they can be archived and ultimately preserved for future generations.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2024, 36 months
Coordinator: Gael Obein, CNAM		Tel: +33 629 553 404
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CNAM, France	9. DTU, Denmark	15. BASF, Germany
2. Aalto, Finland	10. Inria, France,	16. CI, New Zealand
3. CMI, Czechia	11. KU Leuven, Belgium	17. HOLO3, France
4. CSIC, Spain	12. UA, Spain	
5. DFM, Denmark	13. UJM, France	
6. PTB, Germany	14. UNIZAR, Spain	
7. RISE, Sweden		
8. TUBITAK, Türkiye		
Associated Partners:		
18. METAS, Switzerland		
19. Rhopoint, United Kingdom		



Publishable Summary for 23NRM01 SBS Uncert

Support for standardisation of sample-by-sample waveform uncertainty computation

Overview

Today's key technologies for communications are based on the analysis of digitally modulated signals, used to describe, distribute and process information. Additionally, Europe's aim of being the first carbon-neutral continent requires an increased integration of renewable energy into the grid. Measuring the alterations of electrical waveform from its initial generation to its final reception plays a vital role in many industries, e.g. the telecommunications and the power grid industry. Waveforms can be affected by various factors including non-ideal hardware and effects from the transmission channel response. For a common understanding of such signals, IEC TC 85 has developed standards on the measurement and calculation of waveform parameters and the corresponding uncertainties. However, sophisticated applications require extension of the existing standards to cover full waveforms instead of waveform parameters only. This project will develop methods for the calculation of sample-by-sample waveform uncertainties, provide examples and guidelines for the correction and reconstruction of waveforms, disseminate efficient algorithms for the data processing and deliver its results to IEC TC 85.

Need

The standards IEC-60469 and IEC-62754 specify methods for the computation of the temporal and amplitude parameters and their associated uncertainty for step-like and impulse-like waveforms. Within the current revisions, measured waveforms are described by a set of parameters together with a measurement uncertainty.

For a complex system with many degrees of freedom, the reduction of a highly structured waveform to a small set of parameters is insufficient. Two otherwise strongly differing waveforms may go along with identical subsets of parameters. Moreover, the approximation of a waveform via a reduced set of parameters constitutes a significant source of error for subsequent steps of data analysis. For accurate uncertainty propagation as well as signal reconstruction, detailed knowledge of the measurand is required. This may be realised by delivering a mean measured waveform and a measurement uncertainty for each sample of this waveform. Additionally, complex measurement systems and data processing schemes often incorporate data from different domains (time or frequency). To exchange and convert data from and within such instruments, only a full-waveform-based approach prevents data misinterpretations and loss of accuracy.

To ensure applicability for modern instruments and to foster reliable international research and development, industrial production, and quality control in the field of waveform analysis, the existing standards need to be extended. This project will focus on the development of a multivariate sample-by-sample uncertainty analysis for electrical waveforms that includes real-time measurement effects, environmental effects, waveform correction for known amplitude and time base errors of the measurement system, and waveform reconstruction achieved by deconvolution of the measurement system impulse response from the corrected waveform. By including the requirements of the European industrial end users and directly submitting the results to the IEC TC 85 WG 22 internal project group, the standardisation process is ensured to reflect European positions.

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: August 2024

Objectives

The overall aim of the project is to underpin standardisation of electrical signal waveform reconstruction and correction techniques and sample-by-sample uncertainty propagation, enabling stakeholders to apply the standards for their applications.

The specific objectives of the project are:

1. To assess the signal quality along the data generation/transmission/reception path of advanced measurement instruments through the establishment of a multivariate and sample-by-sample measurement uncertainty analysis. To evaluate the amplitude and time base measurement uncertainties for each datum (sample) in the time-varying electrical signal waveform for equivalent time domain, sampled time domain and frequency time domain instrumentation. To provide mechanisms to map the uncertainties from one domain into the other. To implement computational models of distinct measurement scenarios, made available via an online platform.
2. To develop validated data processing methods for the correction of real-time measurement and environmental effects, waveform corrections for known amplitude and time base errors of the measurement system, and waveform reconstruction. To develop an accurate representation of the actual signal and perform multivariate uncertainty analyses on the associated measurement corrections. To implement the data processing methods as software libraries, made available via an online platform for users from, e.g., ICT and power grid management industry.
3. To develop validated computationally fast waveform-correction methods including measurement-uncertainty-analysis. To implement the data processing methods as software libraries, made available via an online platform for users from, e.g., ICT and power grid management industry.
4. To contribute to the revision of IEC-60469:2013 and IEC-62754:2017 and the development of new documentary standards by providing the data, methods, guidelines and recommendations, which are necessary for the standardisation of waveform correction procedures, to IEC TC 85 WG22. Outputs should be in a form that can be incorporated into the standards at the earliest opportunity and communicated through a variety of media to the standards community and to end users.

Progress beyond the state of the art and results

To assess the signal quality along the data generation/transmission/reception path of advanced measurement instruments

Complex electrical signals typically suffer from specific, system-dependent distortions during generation, transmission and reception. These distortions need to be determined precisely and systematically to be considered for data correction and reconstruction of full waveforms. They can affect the measurement uncertainty in non-trivial ways, not adequately described by the use of univariate measurement models. The project will progress beyond the state of the art by setting up measurement models for specific devices and systems. The modelled influence factors will be characterised experimentally. Multivariate measurement uncertainty propagation will be established, resulting in a sample-by-sample measurement uncertainty for the resulting model waveforms. Data sets and models will be submitted to the standardisation bodies, to be incorporated in the extensions of current documentary standards such as the IEC-62754.

To develop validated data processing methods to correct/reconstruct waveforms and to associate a sample-by-sample measurement uncertainty

When working with full waveforms instead of parameter-based descriptions, correction and reconstruction with respect to the aforementioned distortions generally require sample-by-sample data processing. Non-trivial methods are used, e.g., to combine time-domain and frequency-domain data or to deconvolve system response functions. Based on model implementations and characterisation experiments, the project will progress beyond the state of the art by setting up and implementing full-waveform-based correction- and reconstruction procedures for various use -cases. Multivariate uncertainty propagation will be included to associate waveforms with a sample-by-sample measurement uncertainty. Thorough validation of the methods will be realised by inter-device comparisons and by processing measurement data as well as modelled device responses.

To offer computationally fast data processing methods applicable to actual use cases

Full-waveform-based data processing with multivariate uncertainty propagation is not yet established within the stakeholder community. The project will progress the state of the art by implementing software libraries and setting up an online-showroom/data-exchange platform for actual use cases to make direct uptake of the developed methods by the target community easier. Moreover, the available data processing methods typically face computational limitations when applied within actual measurement scenarios. The project will progress the state of the art by focusing on the development and implementation of alternative, computationally less complex approaches. The comparison of different methods, validation results as well as hardware-specific analysis will be summarised in user guidelines.

Outcomes and impact

Outcomes for industrial and other user communities

This project will develop waveform correction and reconstruction methods for typical measurement and calibration scenarios of the target groups such as ICT equipment manufacturers or power grid industries. It will address full-waveform-based electrical signal processing as opposed to the parameter-based description currently included in documentary standards. Worked examples for multivariate uncertainty propagation will be generated, demonstrating significantly improved data interpretation and analysis capability for highly structured and complex waveforms. The methods and findings will be passed towards IEC standardisation bodies, to be included in the development of new standards on sample-by-sample uncertainty propagation.

Typical measurement distortions such as hardware impairments, transition effects and measurement artefacts will be investigated using models and characterisation experiments. For distinct applications, the consortium will propose, implement, validate and provide open access to waveform correction and reconstruction procedures, utilising data interfaces adapted to industrial needs. Additionally, ready-to-use software packages will be generated, time-efficient data processing will be analysed, and hardware-tailored solutions proposed. For the industrial, normative and scientific environments, a direct link between actual measurement activities and standardised data processing will be established.

Guidelines will be set up and disseminated. A digital showroom, workshops, online courses, conference- and journal publications will enable industrial stakeholders, including manufacturers of signal generation and measurement devices as well as end users and calibration laboratories, to directly uptake the project results.

Outcomes for the metrology and scientific communities

The new methods will result in improved calibration procedures for electrical waveforms and possibly updated CMC entries in the future. European metrology infrastructure is strengthened in the international metrology community by replacing or extending current calibration methods used for the parameter-based description of electrical waveforms.

Guidelines, conference contributions and journal publications on the computation of sample-by-sample waveform uncertainty as well as waveform reconstruction and correction will be published. Academia and R&D laboratories will be able to process their measurement data following the specified methods and thus will immediately underpin reliable research and development in the field of electrical signal processing.

Outcomes for relevant standards

The results will be submitted directly to IEC TC 85 WG 22, addressing the extension of the standards IEC 60469:2013 and IEC 62754:2017 as requested by the working group convenor. Regular exchange with IEC TC 85 WG 22 members ensures aligned development of both project outputs and the standards development. The project results on waveform reconstruction and correction as well as sample-by-sample uncertainty calculation will be tailored towards a draft of a new documentary standard.

Within IEEE Instrumentation and Measurement/Waveform Generation, Measurement, and Analysis TC10, the results of this project will be promoted with emphasis on their importance for IEEE 1241-2010TM, IEEE P2414TM and IEEE 1057-2017TM. The findings will be disseminated towards IEEE Microwave Theory and Techniques Society WG Modulated Signal Measurement Uncertainty. The maintenance of IEEE 1765 Recommended Practice for EVM Measurement and Uncertainty Evaluation will be supported by the outcomes of the project.

The project will address communications systems using electrical supply lines via CENELEC TC219 and supports the analysis of electromagnetic interference phenomena present on electricity supply network as well as Power Quality measurement methods within IEC TC 77 SC 77A (IEC 61000-4-30:2015). Moreover, IEC TC 47/SC 47A maintaining IEC 60748-4-3 will be addressed through the project's results.

Longer-term economic, social and environmental impacts

The project will promote standardisation in the field of waveform metrology, which immediately fosters technology and product advancement. Utilising full waveforms with sample-by-sample measurement uncertainty instead of parameter-based descriptions will allow for enhanced product comparisons and performance tracking, as well as thorough device calibration and traceability in the wide market sector of signal generation and detection devices. Harmonisation on a global level of the test and computational methods that are used, will directly contribute to the growth rate of the gross domestic product. The project will specifically address use cases of the main target industries such as ICT and power grid management. ICT is known to be one of the most important sectors for economic development since it provides new goods and services, generates novel value-producing opportunities, and provides employment in manufacturing. Monitoring of power grids, validating power transformers, testing of cables and dynamic line rating are typical tasks to ensure reliable electric power transmission and operation within the European energy infrastructure. This specifically addresses the transformation of the electricity market towards a grid based on distributed energy resources. This transformation results in severe stress to the power grid systems, requiring validated, standardised and ready-to-use solutions for real-time monitoring of electrical waveforms to ensure network stability.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 August 2024, 36 months	
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Chief Stakeholder Organisation: IEC TC 85 Measuring equipment for electrical and electromagnetic quantities		Chief Stakeholder Contact: Nicholas G. Paulter Jr.	
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:	
1. PTB, Germany	4. SIQ, Slovenia		
2. CMI, Czechia	5. TUBITAK, Türkiye		
3. LNE, France	6. EMCC, Germany		
	7. Random Red, Croatia		
	8. UPV/EHU, Spain		
Associated Partners:			
9. STRATH, University of Strathclyde			

Publishable Summary for 23NRM02 SMURFnano

Standardised measurements of surface functionalities on nanoparticles

Overview

Engineered nanoparticles have great application potential in fields such as medicine, sensing, catalysis, energy storage, and opto-electronics. The utility and performance of engineered nanoparticles is largely determined by their surface chemistry. However, documented standards to measure such surface chemistry and functionality do not currently exist. Such standards for measuring the surface functionality of nanoparticles are required to support industrial development, quality control and to meet regulatory requirements. Therefore, this project will address this issue by developing (i) fit-for-purpose, validated, and standardised methods, and (ii) reference data and reference materials, for the measurement of the surface chemistry of nanoparticles using advanced measurement methods (X-ray photoelectron spectroscopy (XPS); secondary ion mass spectrometry (SIMS); quantitative Nuclear Magnetic Resonance (qNMR) as well as more cost-efficient, non-surface specific methods (optical and electrochemical methods)).

Need

Engineered nanoparticles with various chemical compositions and surface functionalities are routinely fabricated for industrial applications in medical diagnostics, drug delivery, sensing, catalysis, energy conversion and storage, opto-electronics, and information storage. The function, performance, interaction with biological species, and environmental fate are largely determined by the surface functional groups of the nanoparticles. Therefore, standardised and reliable surface characterisation methods are vital for the quality control of engineered nanoparticles and are needed to meet increasing safety concerns regarding nanoparticle safety. As well as validated traceable measurement methods, end-users need reference data and reference materials for nanoparticle surface functional groups, which will support them in compliance with regulations, e.g. the Registration, Evaluation, Authorisation and Restriction of Chemicals' regulation (REACH 2006/1907) and cosmetic products regulation (2009/1223), depending on the nanoparticle use.

Currently, methods for determining nanoparticle surface properties, including the amount, chemical composition, and homogeneity of surface functionalities and coatings are largely non-standardised. Over the last few years there has been an increase in the number of publications of documentary standards for measuring nanoparticle size and shape, e.g. ISO 19749:2021, ISO TS 21357:2022. However, these standards do not address nanoparticle surface chemistry. A preliminary work item (PWI 19257) in ISO/TC 229 on surface functional groups and coatings on nano-objects has been accepted, but in order for it to progress further it requires the development of validated methods via (international) interlaboratory comparisons (ILCs). ILCs are also required for a PWI on characterising functional groups by conductometry for electrotechnical systems in IEC TC 113. Further to this, input from surface chemical analysis experts is lacking in the Organisation for Economic Co-operation and Development Working Group of National Coordinators of the Test Guidelines programme (OECD WNT) 1.6 on surface chemistry and coatings of nano- and micro-particles. Thus, standardisation organisations, the European Medicine Agency (EMA), and the nanosafety community responsible for guidelines for nanomaterial regulation i.e. OECD have all expressed the need for standardised methods for the quality control of nanoparticles, based on measurements of nanoparticle surface chemical properties using (i) advanced techniques like XPS, time of flight secondary ion mass spectrometry (ToF-SIMS), and qNMR and (ii) more cost-efficient and simpler optical and electrochemical methods.

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
PARTNERSHIP**



Issued: July 2024

Objectives

The overall goal of the project is to perform metrology research necessary to support standardisation in surface chemical analysis of nanomaterials for industrial applications focussing on the quantification of surface functionalities. The specific objectives of are:

1. To develop methods for the quantification of surface functionalities and coatings on nanomaterials. This will contribute to the development of (i) Preliminary Work Item (PWI) 19257 (ISO/TC 229) on surface functional groups and coatings on nano-objects, and (ii) PWI (IEC TC 113) on characterising functional groups by conductometry for electrotechnical systems and (iii) the technical guideline of OECD Working Group of National Coordinators of the Test Guidelines programme (WNT) 1.6 on surface chemistry and coatings of nano- and micro-particles.
2. To develop validated quantitative procedures for measuring the thickness and composition of nanoparticle coatings and other surface functionalisation using electron spectroscopies (e.g. XPS) building upon ISO TR 23173 (ISO/TC 201) and the EMPIR project 17SIP03 ESCoShell. This will form the basis of a full international standard.
3. To perform international interlaboratory comparisons (ILCs) on the quantification and determination of surface chemistry, under VAMAS TWA2 (surface chemical analysis), with different types of nanomaterials with industry-relevant surface functionalities using the methods and procedures developed in objectives 1 and 2. This will include methods such as XPS, ToF-SIMS, and qNMR and non-surface-specific simpler optical and electrochemical methods.
4. Using input from the ILCs from objective 3, to produce and disseminate test and reference materials, as well as reference data and methods, to the nanotechnology community to underpin the development of quality control methods in nanomaterial production. The reference materials will be used to initiate future BIPM CCQM pilot studies, where feasible.
5. To contribute to the standards development work of the technical committees ISO/TC 229, IEC TC 113, ISO/TC 201, and OECD WNT 1.6 to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing, and using the standards, and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Methods for quantifying surface functionalities/coatings on nanomaterials; contributing to PWI for ISO, IEC and OECD.

The last few years have seen an increase in the number of publications of documentary standards for measuring nanoparticle size and shape, e.g. ISO 19749:2021, ISO TS 21357:2022, and OECD Test Guideline No. 125, which have been developed to underpin the EU definition of nanomaterials [Official Journal of European Union 2022/C 229/1], supported by European projects like NanoDefine (Development of an integrated approach based on validated and standardised methods to support the implementation of the EC recommendation for a definition of nanomaterial) and EMPIR project 17NRM04 nPSize. However, these standards do not address nanoparticle surface chemistry. A preliminary work item (PWI 19257) in ISO/TC 229 on surface functional groups and coatings on nano-objects has been accepted but in order for it to progress further it requires the development of validated methods via (international) ILC. ILCs are also required for a PWI on characterising functional groups by conductometry for electrotechnical systems in IEC TC 113. Further to this, input from surface chemical analysis experts is lacking in OECD WNT 1.6 on surface chemistry and coatings of nano- and micro-particles. This project will go beyond the current state of the art by addressing these issues and developing much-needed methods for quantifying nanoparticle surface functionalities and coatings. The project will then provide this input to PWI for ISO/TC 229, IEC TC 113, and OECD WNT 1.6.

Validated quantitative procedure for thickness and composition of nanoparticle coatings forming basis of an ISO standard.

The previous EMPIR project 17SIP03 ESCoShell led to an informative technical report ISO TR 23173 (Surface chemical analysis - Electron spectroscopies - Measurement of the thickness and composition of nanoparticle coatings). However, despite having addressed a knowledge gap in this area, this report only provides information on uniform core-shell nanoparticles which can only be considered as an idealised model for nanoparticle coatings. In addition, ISO TR 23173 does not provide the required methodology for a full standard.

This project will go beyond the current state of the art by developing validated quantitative procedures for measuring the thickness and composition of nanoparticle coatings. This work will be provided to ISO/TC 201 and should lead to a revision of ISO TR 23173 and result in a full ISO standard.

Interlaboratory comparisons on the quantification and determination of nanoparticle surface chemistry.

Over 10 years ago, a VAMAS ILC on measuring the thickness and chemistry of nanoparticle coatings using XPS and low-energy ion scattering spectroscopy (LEIS) was the first attempt to study the reproducibility of measuring the thickness of peptide coatings on gold nanoparticles by surface analytics. Since then, significant work has been undertaken to improve best practices for nanoparticle analysis and XPS calibration, but to date no ILC has assessed the outcome of this work. As part of the H2020 project NanoHarmony an European ILC on nanoparticle surface chemistry is currently taking place, but the ILC is using simple samples and less than 4 surface analytical participants and does not include uncertainty analysis. This project will go beyond this by organising at least two ILCs under the auspices of VAMAS TWA2 involving participants from the project, as well as those from outside the consortium (e.g. NMIs, industry and academia). These ILCs will be used to understand the sources of uncertainty in measurements for the quantification and determination of nanoparticle surface chemistry. Furthermore, the ILC results will be used to try and reduce uncertainty levels as well as to test, validate, and improve the methods developed in this project.

Production and dissemination of test and reference materials and reference data.

Currently, existing reference materials are either bulk materials for calibrating surface chemical analysis instruments or nanoparticles of known size, shape and/or concentration. There are also no reference nanomaterials of known surface chemistry. In this project, the test material developed for the ILCs and the reference data from the ILCs will be assessed and if suitable, disseminated for use as test and reference materials. Additionally, the feasibility of using these reference materials for Pilot Studies in BIPM's Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology Surface Analysis Working Group (BIPM CCQM SAWG) will be evaluated and progressed (if possible).

Outcomes and impact

Outcomes for industrial and other user communities

The results of this project (i.e. validated and standardised methods) and the documentary standards produced from it will support industrial stakeholders in the characterisation, process control, quality assurance, and regulatory evaluation of surface functionalised nanoparticles. Relevant industries include the medical (medical diagnostics, drug delivery) and energy sectors (energy conversion and storage), as well as companies manufacturing nanoparticles for sensing, catalysis, and opto-electronics. This project's results will help to provide stakeholders in these industries and sectors with (i) confidence in the design of novel nanomaterials with precisely tuned surface chemistries and functionalities, (ii) to lay the foundations for safe-by-design (i.e. balancing safety with functionality) nanoparticle strategies, and (iii) to better assess safety in nanotechnological production processes (needed for compliance with REACH 2006/1907 and cosmetic products regulation (2009/1223).

The standardised methods, developed and validated in this project, will help to deepen knowledge on nanoparticle surface structure-function relationships in European nanotechnology industries. This will facilitate the design of novel nanomaterials with improved function and performance and to improve the quality control of nanoparticles. This improved understanding of nanoparticle surface chemistry will also be directly exploited by the industrial participants involved in this project (EVO and PolyAn). EVO and PolyAn will also take part in the project's ILCs. Furthermore, the project will also invite industrial stakeholders to take part in its two ILCs to promote awareness of the project's methods and their uptake.

In addition to this, the project's test and reference materials for measuring nanoparticle surface functionalities will be made available to industrial stakeholders via the BAM webshop, and the project's reference datasets will be made available to stakeholders via an open access repository e.g., Surface Science Spectra.

The project will engage with industrial stakeholders via their inclusion in the project's ILCs and the setup of a stakeholder committee, that will be used to gain feedback on the project, to help maximise impact (project promotion) and to facilitate the uptake of the project's outputs. The stakeholder committee will include representatives from industry, manufacturing, analytical laboratories, and regulation and standardisation organisations.

Outcomes for the metrology and scientific communities

This project will expand the measurement capabilities of the NMIs/DIs in the consortium so that they can provide new and improved metrological services for the surface analysis of nanoparticles. Additionally, the project will support the metrology and scientific communities via knowledge exchange with on-going EU projects such as those in the European Nanosafety Cluster, which is an open platform for the coordination of nanosafety research in Europe. In particular, the project's reference datasets for measuring nanoparticle surface functionalities will be presented to the European Nanosafety Cluster. The project will also collaborate and share results with other Partnership projects such as 22HLT04 MetrINo on Metrology for innovative nanotherapeutics. Further to this, the project will engage the metrology and scientific communities by investigating the feasibility of using the project's reference materials for future pilot studies at BIPM CCQM.

The project also intends to engage with the metrology and scientific communities via EURAMET's European Metrology Networks (EMNs) such as EMN Traceability in Laboratory Medicine.

Finally, to promote the uptake and acceptance of the project's results, this project will publish the results in peer-review publications, present the results at conferences, organise two stakeholder workshops, at least two training webinars e.g. on XPS and qNMR and a video for e-training on the use of the new methods for nanoparticle quality control.

Outcomes for relevant standards

The results from the project will directly feed into 4 standards in 4 different standards committees (ISO/TC 229, ISO/TC 201, IEC TC 113 and OECD) and will result in standardised methods for the surface chemical analysis of nanoparticles. The project's outcomes will be disseminated via (i) PWI 19257 to ISO/TC 229 on surface functional groups and coatings on nano-objects, (ii) PWI to IEC TC 113 on characterising functional groups by conductometry for electrotechnical systems, (iii) the technical guideline of OECD WNT 1.6 on surface chemistry and coatings of nano- and micro-particles, and (iv) a validated quantitative procedure for the measuring the thickness and composition of nanoparticle coatings and other surface functionalisation using electron spectroscopies building for ISO TR 23173 (ISO/TC 201).

Further to this, the project will engage with ISO/TC 24 SC4 'Particle Characterisation', VAMAS TWA2 Surface Chemical Analysis for the hosting of its two ILCs, and BIPM CCQM SAWG for future pilot studies.

During the project, the consortium will also actively collaborate with the project's chief stakeholder from ISO/TC 229 JWG2. Input from the chief stakeholder will be used in the drafting of normative documents (i.e. PWI) to increase the likelihood of their success and acceptance.

Longer-term economic, social and environmental impacts

In the longer term this project will support advances in European nanotechnology, particularly in the medical and energy sectors. Uptake of the project's results by industry and standardisation bodies should facilitate nanoparticle compliance with regulation, increase end user confidence in nanoparticles and accelerate their use in end products. Given that the global nanotechnology market is projected to reach more than 30 billion € in 2030, this represents huge business opportunities for Europe in market sectors such as medical diagnostics, sensing, catalysis, energy (storage and conversion), and opto-electronics. The increased use and increased availability of safe and functional nanoparticles should also contribute to advancements in these sectors, leading to improved and safer products and services.

This project will also support positive social impacts in a variety of sectors where functional nanoparticles can be used e.g. medical diagnostics, imaging, targeted drug delivery, and therapy. Hence this project should help to advance healthcare by enabling better treatments with reduced side effects.

Nanoparticles can also be used in sensing technologies for environmental monitoring, food safety, and security applications. Thus, this project will support the safe use of nanomaterials and related end products in these areas by the development of sustainable and safe-by-design strategies. By controlling the surface chemistry of nanoparticles, researchers can optimise their properties to minimise environmental impact. For example, engineered nanoparticles with improved functional properties can be used in energy production, conversion, and storage systems that are more efficient and environmentally friendly, and the safe use of nanomaterials can help reduce waste generation and promote sustainable practices.

Project start date and duration:		01 July 2024, 36 months	
Coordinator: Ute Resch-Genger, BAM		Tel: + 49 30 8104-1134	E-mail: ute.resch@bam.de
Project website address:			
Chief Stakeholder Organisation: ISO/TC 229/JWG2 (Nanotechnologies, Measurement and Characterisation)		Chief Stakeholder Contact: Naoyuki Taketoshi	
Internal Beneficiaries: 1. BAM, Germany 2. INRIM, Italy 3. RISE, Sweden		External Beneficiaries: 4. EVO, Germany 5. JSI, Slovenia 6. PolyAn, Germany 7. UNIVIE, Austria	
		Unfunded Beneficiaries: 8. FUB, Germany 9. PTB, Germany	
Associated Partners: 10. LGC, United Kingdom 11. NPL, United Kingdom 12. NRC, Canada			

Publishable Summary for 23NRM03 BioAirMet

Standardisation of bioaerosol monitoring for air quality and climate modelling

Overview

Biological aerosols (mainly pollen and fungal spores, but also bacteria, viruses and plant debris) are ubiquitous in the atmosphere. They influence the hydrological cycle and climate, and some of them are known human and plant pathogens and/or allergens. Newly developed systems to monitor airborne biological particles, based on automatic bioaerosol monitors and machine learning, have revolutionised the field by providing real-time information on particle number concentration and taxa/species. However, traceability is incomplete and measurement uncertainties are poorly understood. This project will provide input to a new documentary standard on automatic pollen and fungal spore monitoring within the CEN/TC 264/WG 39 and will develop quality assurance procedures for this new class of bioaerosol monitors.

Need

Biological aerosols are released into the air by plants, fungi and other living organisms as part of their reproductive or decomposition cycles. They are ubiquitous in the atmosphere, although their concentration and composition can vary significantly in time (e.g., night vs day) and by location (e.g., park vs residential estate). Besides their biological importance, many bioaerosols, especially pollen and some fungal spores, have an allergenic or pathogenic effect on humans. Pollen allergy and asthma are some of the most common chronic diseases, affecting between 15 %-40 % of the European population (forecasted to be 50 % by 2050), with estimated direct and indirect health costs exceeding €50 billion per year. Bioaerosol monitoring has therefore become essential as it underpins practical mitigation and adaptation measures. The data are required, and used, by physicians for diagnosis, treatment and clinical studies as well as for empirical and numerical pollen forecasts, which aid allergy sufferers to effectively plan their activities and medication intake.

Bioaerosols can act as cloud condensation nuclei as well as ice nuclei, influencing the hydrological cycle and climate. Moreover, information on bioaerosols is crucial for agriculture and forestry, where real-time data about the presence of pathogens, mostly fungi, are necessary for protecting agricultural production. Pollen monitoring is needed to underpin ecological studies on vegetation shifts and invasive species.

Originally, bioaerosol monitoring networks were based on offline manual methods. These methods suffer from poor time resolution (typically 24 hours) and long delays in data availability (typically 7-9 days). Recent technological developments and machine learning have made it possible to automate bioaerosol monitoring, revolutionising the information that can be made available to end-users.

Automatic bioaerosol monitors are not fully calibrated as new methods need to be developed. The machine learning algorithms need to be adequately trained as they are currently trained with particles supplied to the devices under generic laboratory conditions or even outdoors (e.g., rooftops of meteorological institutes), with no strict control over the environmental conditions. Also, strong deviations are observed due to different measurement principles being in use among the instruments and the data outputs are not comparable, or they require some transformation, making the process time consuming and imprecise (e.g., some machines report coarse particle number concentration, others only particle counts or size classes). These approaches need to be standardised. Once the calibration process is validated and deviations reduced, the production of a new

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership



Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP



Issued: June 2024

documentary standard by CEN/TC 264/WG 39 will be required to make the new processes available to stakeholders (e.g., bioaerosol monitoring networks and instrument manufacturers).

Objectives

The overall objective of this project is to provide input to a new documentary standard on automatic pollen and fungal spore monitoring within the CEN/TC 264/WG 39 and to develop quality assurance procedures for state-of-the-art bioaerosol monitors. The specific objectives of the project are:

1. To further develop two traceable methods (light scattering and particle flow visualisation) for the calibration of automatic bioaerosol monitors with respect to particle size and number concentration (target expanded uncertainty $\leq 15\%$). To provide clear guidelines to end users about the specifications, limitations and application range of each primary method.
2. To develop methods for training and validating machine learning (ML) algorithms, which identify airborne pollen taxa and fungal spore species in real-time, based on the collection of bioaerosol particles from natural sources, appropriate conditioning/treatment in the laboratory and controlled re-dispersion in air. To develop methods for quantifying the accuracy of the algorithms and for deriving a combined uncertainty arising from uncertainties in both particle counting and particle identification (target expanded uncertainty $\leq 30\%$).
3. To standardise the data output, interface and metadata of automatic bioaerosol monitors. To develop guidelines on data storage, handling and distribution, ensuring data availability and accessibility compliant with EU environmental regulations, in particular with the [Inspire Directive](#).
4. To contribute to the development of a new standard on automatic pollen and fungal spore monitoring within the CEN/TC 264/WG 39 – Sampling and Analysis of Airborne Pollen Grains and Fungal Spores, and to contribute to the revision of existing standards published by CEN/TC 264/WG 28 – Measurement of Airborne Microorganisms in Ambient Air.
5. To address stakeholder needs regarding automatic bioaerosol monitoring highlighted at the [BIPM/CCQM Workshop on Particle Metrology](#) and establish strong collaboration with EMN Pollution Monitoring. To facilitate the uptake of the technology and measurement methodologies developed in the project by the [EUMETNET AutoPollen](#) community, the EU Horizon Europe project SYLVA, (national/regional) bioaerosol monitoring networks and instrument manufacturers.

Progress beyond the state of the art and results

The technical results that are expected to be delivered by this project are as follows:

1. Further development and standardisation of traceable methods for counting of micrometre-sized bioaerosol particles (pollen and fungal spores)

Existing methods for the determination of airborne particle number concentration, based on reference optical particle counters, will be standardised in the particle size range up to at least $50\text{ }\mu\text{m}$ and at particle number concentrations above $0.5\text{ particle per cm}^3$ with a target expanded uncertainty of $\leq 15\%$. A new reference method based on particle tracking and velocimetry will be applied, for the first time, on the sampling and counting of bioaerosol particles, extending the detected size range up to about $80\text{ }\mu\text{m}$ with a target expanded uncertainty of $\leq 30\%$.

2. Development of procedures for quantifying the performance of machine learning algorithms and the uncertainties related to particle taxon identification

Methods for training machine learning algorithms will be extended to include temperature- and humidity-controlled samples as well as atmospherically aged particles. Procedures for comparing the outputs of ML algorithms will be developed, the sensitivity of ML algorithms to factors that affect field deployment will be investigated and uncertainties, in taxon identification, will be quantified. Guidance on how to assess a ML taxon classification algorithm will be prepared to share good practice and to give users confidence in the suitability of algorithms for their area. The sensitivity analysis will be used to suggest recommendations for the creation of training and testing datasets for ML algorithms for field deployment.

3. Standardisation of the data output, interface and metadata of automatic bioaerosol monitors and the development of guidelines on data storage, handling and distribution

Level 0 (unprocessed) and Level 1 (processed and calibrated) data will be standardised, and the project participants will formulate recommendations regarding specific data fields, metadata descriptors, units of measurement, uncertainty reporting guidelines and the overall structure of processed data. Furthermore, practices related to distributed data, database management, data accessibility and version control will be reviewed within the context of automatic bioaerosol monitors. A clear and effective set of recommendations will be developed to optimise the organisation, accessibility and traceability of data across various stakeholders in accordance with the EU environmental regulations, in particular with the [Inspire Directive](#).

4. Contribution to a new CEN/TC 264/WG 39 standard on automatic bioaerosol monitoring and the revision of existing standards published by CEN/TC 264/WG 28

Currently, the only documentary standard on the measurement of ambient pollen and fungal spores refers to the manual method based on the use of collection impactors and offline light microscopy (EN 16868:2019 "Ambient air - Sampling and analysis of airborne pollen grains and fungal spores for networks related to allergy - Volumetric Hirst method" by CEN/TC 264/WG 39). Another document of importance is the technical specification (TS) CEN/TS 16115-1:2011 "Ambient air quality - Measurement of bioaerosols - Part 1: Determination of moulds using filter sampling systems and culture-based analyses" by CEN/TC 264/WG 28 for the same manual methods as with WG 39. The results of this project will feed directly into the new technical specification (to be later upgraded to a full standard) which is currently being developed by CEN/TC 264/WG 39 on real-time, automatic bioaerosol monitoring and into new or updated documents of CEN/TC 264/WG 28.

Outcomes and impact

Outcomes for industrial and other user communities

The early industrial impact of the project will be focussed on the standardisation of aerosol generators, designed and produced in Europe. Swisens have recently developed a bioaerosol generator (known as the Swisens Atomizer) and METAS was directly involved in the development and validation of a novel oxidation flow reactor (known as the OCU). By combining the Swisens Atomizer with the OCU to produce atmospherically aged bioaerosols, the application range of both generators will be extended. Further standardisation of the generators in new fields of research and demonstration of how these can be incorporated into a single setup for training ML algorithms will further boost sales in Europe and worldwide. Europe has a strong presence in the manufacturing of automatic bioaerosol monitors. The availability of traceable calibration for such instruments will be a direct benefit for existing instruments and on the development of new designs. The improved accuracy of bioaerosol measurements will stimulate demand and production. Europe is leading the automation of bioaerosol monitoring stations, with more than 400 automatic instruments expected to be installed across Europe in the next few years.

Efficient and accurate bioaerosol monitoring will benefit pollen monitoring, which can be used to forecast the production of certain crops, e.g., olives or oak. This can provide useful information to agricultural end-users, helping them e.g., to fix prices and manage crop harvests. Bioaerosol monitors can also be used indoors or in workplace environments that may be contaminated with pathogenic organisms (e.g., organic waste treatment, livestock and poultry farming, arable farming). This project will develop procedures for validating mid-cost bioaerosol monitors which can distinguish between pathogenic and non-pathogenic particles and alert the workforce when a specific target value has been exceeded. Real-time viable particle counters provide real-time counts of total and viable particles in pharmaceutical manufacturing environments to reduce aseptic interventions, improve root-cause investigations and increase process knowledge. Such instruments will be calibrated for the first time in this project, providing valuable information to pharmaceutical and biotechnology industries operating clean rooms.

The vast majority of automatic bioaerosol monitors (POMO-BAA500, SwisensPoleno, Rapid-E, BeeNose, Aerotape and others) are designed and produced in Europe. This project will enhance the end users' confidence in these instruments through standardisation and certification, which will promote sales and help European manufacturers assume a leading role in the global market.

Outcomes for the metrology and scientific communities

Standardising the generation of fresh and aged (i.e., processed) bioaerosols in the laboratory will enable NMIs and DIs to offer new calibration procedures for a variety of instruments, such as automatic bioaerosol monitors for ground-based measurements, aerosol LiDAR systems which determine the vertical profile of aerosols in the atmosphere and portable particle counters and size spectrometers for high-altitude (free troposphere) measurements. In addition, the generation of well-defined bioaerosols in the laboratory is essential for performing controlled health-related studies, e.g., in vitro toxicology and in vivo inhalation studies. Experiments with laboratory-generated bioaerosols, under controlled conditions, can provide information on the causal link between the particles we breathe and the down-stream health effects. They can also complement epidemiological studies.

Since aerosol metrology is a relatively new scientific topic, compared to gas analysis and other relevant disciplines, this will provide a much-needed uplift for aerosol laboratories, helping them to build new scientific networks, and to grow their research collaborations and service spectrum. Moreover, the results of this project will feed directly into regional/national bioaerosol monitoring networks (e.g., ePIN, SwissPollen, AirAllergy, Met Eireann Network, FinBio). The availability of standardised calibration procedures for bioaerosol monitors is a key benefit from the project and will increase the accuracy and comparability of their data. This in turn will lead to better pollen forecasts for physicians and clinicians, better fungal spore forecasts for ecology and agricultural research, reliable data for the modelling of bioaerosols in the atmosphere and robust emission inventories for airborne pathogens and their regulation.

The results of this project will feed directly into European automatic bioaerosol monitoring networks and they will improve data accuracy by reducing measurement uncertainties from >60 % down to <30 % to address stakeholder needs. The know-how in the training of ML algorithms will find applications in other areas of aerosol sciences, e.g., in the identification of various black carbon (BC)-containing particles, and potentially in other applications that use ML for image-based classification. Further, the consortium will interact closely with the EU Horizon Europe project SYLVA (2023-2026), which is establishing the technological background for European bioaerosol networks.

Outcomes for relevant standards

The results of this project will feed directly into the new CEN/TC 264/WG 39 technical specification on the automatic bioaerosol monitoring of pollen grains and fungal spores, which will be the very first standard worldwide on this scientific/technical subject. The project will also contribute to the revision of existing standards published by CEN/TC 264/WG 28 – Measurement of Airborne Microorganisms in Ambient Air. The outputs of this project will contribute to the development of a new CEN technical specification (and later a standard) on "Near real-time measurement methods for monitoring airborne pollen and fungal spore concentrations" within CEN/TC 264/WG 39. This standard will complement, or even replace in the future, the EN 16868:2019 standard for the manual method: Sampling and analysis of airborne pollen grains and fungal spores for networks related to allergy - Volumetric Hirst method.

Information on progress, and results, from the project will also be disseminated to other standardisation bodies and committees and feedback sought, such as to ISO/TC 24/SC 4/WG9 – Single particle light interaction methods, AFNOR/X43D - Air quality monitoring in ambient air, EURAMET Technical Committee for Metrology in Chemistry (TC-MC) WG Gas Analysis, BIPM Consultative Committee on Quantity of Matter (CCQM) - WG Gas Analysis - Task Group on Particle Metrology. When possible, representatives on the corresponding committee or WG from the participating NMIs will jointly ask to include a point in the agenda to briefly present the outputs of the project related to the WG activities and ask for comments from the other committee/WG members.

Instrument standardisation and certification will also pave the way for the development of European legislation on bioaerosol monitoring, e.g., by setting target limits for highly allergenic or pathogenic bioaerosols in the European Air Quality Directive.

Longer-term economic, social and environmental impacts

The direct impact of the research will be (near) real-time, more accurate and comparable measurements of bioaerosols, drastically improving the current status of the manual monitoring networks in Europe through the development and standardisation of methods for calibrating automatic bioaerosol monitors. Calibration

procedures with regards to both particle number concentration and particle identification will be standardised to achieve full traceability to the SI (International System of units). Note that this will be the very first time that full traceability (i.e., particle counting combined with particle identification) to the SI will be achieved in the field of aerosol sciences.

Indirectly, the impact would be very widespread. In terms of scientific benefits, the improved measurements would fit into EU atmospheric aerosol projects, refining climate change models, and improving the quality of conclusions from cohort health studies, which are looking at the health effects of bioaerosols. The ML algorithms standardised in this project could also find novel applications in bioaerosol monitoring in indoor and workplace environments as well as in air pollution monitoring, e.g., in black carbon source apportionment.

An accurate and timely bioaerosol forecast, combined with the traditional weather forecast, will inform the vulnerable population on the particle number concentration of pollen and fungal spores in ambient air, and advise citizens to take necessary measures (e.g., contact avoidance and/or preventive medication) in the case of high pollen and/or fungal spore counts. It will also underpin allergy treatment by enabling a more targeted and efficient use of anti-allergy medication. In terms of socio-economic benefits, the project's outputs will provide a basis for better city management and planning. Urban green spaces are a key element in the design of modern cities, since they promote human interaction with nature and help to fight heatwaves in cities, thus improving human health. However, lack of planning in the design of public spaces, unfortunate choices of ornamental species and the interaction of pollen with air pollutants have been among the factors triggering allergy and asthma, two of the most widespread chronic diseases in urban populations. Ultimately, the output of this research will have significant benefits on human health within Europe, helping the more than 100 million Europeans who suffer from allergies. Considering the enormous costs of allergies and asthma in terms of hospitalisation and lost labour (> €55 billion per annum due to absence from work or reduced productivity), even a small decrease in these costs through prevention and better treatment will save the EU billions of € on an annual basis, largely exceeding the initial investments in the network's development and standardisation. Real-time information about fungal spores in combination with high resolution models could also mean more targeted fungicide use (both in time and space), which will not only reduce costs, but also environmental damage. The costs associated with crop loss from fungal pathogens are on a similar scale to the impact on human health.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months	
Coordinator: Tobias Klein, PTB		Tel: +49 0531 592 5240	
Project website address: https://www.ptb.de/epm2023/bioairmet		E-mail: tobias.klein@ptb.de	
Chief Stakeholder Organisation: CEN / TC 264 / WG 39		Chief Stakeholder Contact: Gilles Oliver	
Internal Beneficiaries:		External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany		6. Oberon, France	-
2. DFM, Denmark		7. Sciensano, Belgium	
3. FMI, Finland		8. TUM-MED, Germany	
4. LNE, France			
5. RISE, Sweden			
Associated Partners:			
9. EDI, Switzerland			
10. METAS, Switzerland			
11. NPL, United Kingdom			
12. Swisens, Switzerland			

Publishable Summary for 23NRM04 NoQTeS

Normating colour-centre-based quantum sensing technology towards industrial application and standards

Overview

Solid-state quantum sensors (QSS) have the potential to measure several physical quantities with unprecedented spatial resolution and high sensitivity. As such, they are emerging candidates for potential applications in a plethora of fields e.g. high precision electric magnetic and radiofrequency measurements, gravimetry, climate research, hydrocarbon and mineral exploration, navigation, medicine (brain imaging, heart imaging) and metrology. Nitrogen-Vacancy (NV) centres are photoluminescent point defects in diamond, which have high potential for future uptake as they present the highest Technology Readiness Level (TRL) amongst solid state atomic-scale sensors. However, standardised methods which would enable the adoption of solid state quantum sensors, in particular NV centres, are still missing. This project aims to address this need by developing standardised techniques for the creation and characterisation of QSS based primarily on NV centres in diamond for nanoscale and high sensitivity sensing of electromagnetic fields, temperature or pressure. This will be done in synergy with the needs expressed by CEN-CLC JTC-22 to promote early uptake of the project outputs and foster future uptake of novel solutions, including colour centres in other bulk or 2-D semiconductor materials (e.g. Si, SiC, hBN).

Need

Solid state QSS have a recognised level of maturity and potential applications in magnetometry, thermometry, biosensing, etc, as identified by the CEN/CENELEC Focus Group on Quantum Technologies in their roadmap and standardisation needs, which prompted the creation of a dedicated technical committee (CEN/CENELEC JTC-22). The existence of a quantum sensing technology standard that stakeholders can adhere to, would significantly de-risk further investments in the quantum technology sector, and is therefore urgently required.

For this to be possible, NV-based sensors must be produced using reference (well established) methods, which enable to control key properties such as doping, native defects concentration or position of colour centres. Additionally, standardised methods must be developed for the characterisation of NV-based sensors, and reproducible procedures for producing and testing non-NV sensors/ single photon emitters must be targeted. To obtain sensors based on colour centres in diamond with enhanced performance, current techniques and methods must be extended to include enhancement of the excitation source and of the readout. This work and progress must then be shared with CEN-CLC JTC-22, to feed into the development of normative documents related to the QSS.

Objectives

The overall objective of the project is to develop traceable measurement and characterisation methods for quantum sensing technologies necessary to support standardisation of devices based on colour centres in diamond.

The project objectives are:

1. To implement reference methods in the production of NV-based sensors, covering properties (e.g., doping, native defects concentration or position of colour centres). Additionally, to develop

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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EURAMET

Issued: June 2024

methods for the standardised characterisation of NV-based sensors, including the definition of measurement procedures, figures of merit and performance in terms of key parameters. This will include methods for sub-micron localisation (spatial resolution <500 nm) of point defects, quantification of their formation yield (> 10 %) via controlled ion implantation in diamond, and 3D confocal mapping, and traceability.

2. To develop and validate reproducible procedures for producing and testing non-NV sensors/single photon emitters (e.g. novel defects in diamond, point defects in Si, SiC, 2D materials (hBN), semiconductor quantum dots (e.g. InAs, etc.). This will include the development of a benchmarking with respect to NV sensors, in terms e.g. of contrast, brightness, emission wavelength.
3. To extend current techniques and methods for the production of sensors based on colour centres in diamond, with enhanced performance. This will include enhancement of the excitation source (e.g. squeezed light excitation for reduction of pump noise level, coupling of the photoluminescent (PL) sensors to photon-collection-enhancing structures) and enhancement of the readout (e.g. machine-learning based protocols) to optimise the performance based on the specific signal being measured and feasibility study on synchronous detection of PL and electric-activity in biological samples (e.g. tests of background PL emission of Multi-Electrode Arrays (MEAs)).
4. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMI/Dis), standards developing organisations (CEN/CENELEC JTC-22) and end users (industry, sensor manufacturers, calibration facilities) and EMN-Quantum.

Progress beyond the state of the art and results

EMPIR project 20IND05 QADeT developed methods for: (i) engineering individual colour centres in diamond and other suitable materials in a controlled way; (ii) characterising colour-centre based Qs and (iii) developing of dedicated detectors for measurement traceability in the photon-counting regime. An important result was that CEN/CLC FGQT members of the consortium were able to contribute significantly to the draft of the first release of its roadmap on Quantum Technologies, in particular with prominent role in its section related to colour centres as enabling technology for quantum sensing.

This project will build on the effort started in the previous project by providing standard methods for the development and characterisation of colour-centre based Qs that will, on the one hand, acknowledge the specific needs and pre-normative gaps in QT and quantum metrology fields and, on the other hand, will contribute to the development of standard documents and regulations through synergy between the consortium and CEN/CLC JTC-22 and UNI/CT-535.

Objective 1: Methods for the production and characterisation of NV-based sensors

This project will develop new methods to fabricate substrate materials with a controlled concentration and distribution of NV centres, using both conventional and a wide range of innovative techniques such as controlled ion implantation. In parallel, methods for the standardised characterisation of NV-based sensors will be developed and summarised in a good practice guide, which will include the definition of measurement procedures, figures of merit and performance in terms of key parameters.

Objective 2: Procedures for producing and testing non-NV sensors including benchmarking with respect to NV sensors

Group IV elements (Si, Ge, Sn and Pb) in bulk diamond and nanodiamonds will be systematically implanted, allowing the production of novel colour centres. Ensemble PL spectroscopy will be used to study the optical activity of the implanted ion species. InAs (Indium arsenide) quantum dots (QDs) will be fabricated using in-situ stencil masks to create a substrate with known QD locations and successively embedded in GaAs nanophotonic waveguides to be characterised in terms of the quantum coherence and indistinguishability properties of the fabricated devices. Furthermore, the possibility to fabricate Qs in host materials other than such as Si, SiC and 2D materials such as hexagonal Boron Nitride (h-BN), will be investigated.

Objective 3: Methods for enhanced performance of sensors based on colour centres in diamond

This project will extend the work carried out in the previous project in terms of noise suppression and performance enhancement of Qs by means of: engineering of methods based on colour-centres in diamond/single-photon sources (e.g. squeezed states excitation, nanostructures emission coupling);

innovative readout techniques including (e.g. methods for investigating the influence of the diamond crystal characteristics on the photo-electric detection of the NV centres magnetic resonances, experimentally adaptive quantum sensing techniques based on Bayesian inference and machine learning); compatibility of detection of Optically Detected Magnetic Resonance (ODMR) and electro-physiology in biological samples.

Outcomes and impact

Outcomes for industrial and other user communities

According to the Strategic Research Agenda of the Quantum Flagship: “Europe has world-leading researchers in most domains of Quantum Technologies but its competitors such as China, US, Canada, Japan or Australia are strong and are massively investing to develop quantum technologies.” This project will run in parallel with other European initiatives such as Quantum Flagship projects (AMADEUS and MUQUABIS) and the EMN-Quantum, and it will contribute to put the European Union in a prominent role in the global challenge to implement quantum technologies at the industrial/commercial level and to create infrastructure for metrological support of quantum products. Furthermore, the field of quantum technologies is now sufficiently mature for developing standardisation and being ready at such an early stage can be an advantage for European Industry.

To promote the uptake of the project outputs by this community, the consortium will invite manufacturers and end-users of quantum sensors and related technology to the workshop that the project will organise and run, to share the results achieved in the project.

Outcomes for the metrology and scientific communities

The existence of standards and regulations for quasi-atomic scale sensors with high sensitivity and efficiency will affect the current status of quantum metrology, providing, as a direct consequence, reliable enhanced measurement capability for several physical observables (e.g. electromagnetic quantities, temperature, pressure, force, etc.) with high sensitivity and extreme spatial resolution. This will have high impact in the measurement science community across several fields, e.g. medical imaging. Fabrication and characterisation methods developed for atom-scale sensors can also be used in the manufacturing of solid-state Fock state sources. This will enable the development of quantum processors based on boson sampling and photonic quantum walks, as well as offering a central resource to boost quantum-enhanced techniques such as quantum radar and sub-shot-noise imaging.

The methods to be developed in the project will have the potential to be used to test and calibrate quantum devices, to expand the capabilities of NMIs and companies and extend the measurement services to the European citizen to include implementations of quantum metrology. These may find applications in biosensing, thermometry, radiofrequency magnetometry, in the characterisation of nanotechnology devices and electric vehicles batteries as well as in navigation systems (with foreseeable application in defence), and detection of toxic substances/pollutants (contributing to the current global challenge of environment monitoring).

Additionally, the single atom-like sensors and related metrology to be developed at the European NMIs will enable the development of a metrological and, in the long term, industrial frame of validation of the related quantum products.

To promote the uptake of the project outputs by this community, the consortium will engage with CEN/CENELEC JTC-22, EMN-Quantum, Quantum Flagship and the European Quantum Industry Consortium. The stakeholder advisory board will be regularly consulted to ensure relevance of the project work and results to the communities.

Outcomes for relevant standards

This project will have direct impact on the standardisation and normative fields. The development of reproducible techniques for quasi-atomic scale sensors with high sensitivity and efficiency will affect the current status of quantum metrology, leading to documentary standards related to the characterisation of prototype devices for quantum products. This will be done in close collaboration with standardisation bodies such as CEN-CENELEC JTC-22 and in agreement with their upcoming standardisation activities as well as in collaboration with the EURAMET Technical Committees and the EMN-Quantum.

Longer-term economic, social and environmental impacts

This project will contribute to the growth and consolidation of the quantum technologies market by contributing to the standardisation of QSS based on diamond and other materials. This will create an ecosystem composed



of NMIs, academia, standardisation bodies and industry that will bring long term benefit society in general. In the longer term, the outputs of the project will benefit different areas (e.g. physics, chemistry, biology, medicine, as well as data storage and processing).

Furthermore, the standardisation of point defect-based quantum sensors, to which this project contributes to, will lead to a number of long-term societal and economic benefits, especially in terms of i) breakthroughs in medical imaging, and drug design and efficacy, leading to corresponding advances in disease diagnosis and treatment as well as in low-cost diagnosis systems; ii) environment benefits through optimised battery management, lower consumption electronics devices or through the reduction of electronic pollution; iii) optimised wireless communications resulting from cognitive radio capabilities being extended to the 5 GHz - 25 GHz frequency range; and iv) the emergence of a new industry and new companies, thus creating new job opportunities. Qs will be at the heart of the Quantum Internet of Things with a strong transformative effect on society in the long term. By facilitating the creation of a broad market for quantum devices and next-generation products, in the long term the project will contribute to in general improvements in services (e.g. healthcare, communication, mobility) in Europe.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 June 2024, 36 months	
Coordinator: Paolo Traina, INRIM		Tel: +39 011 3919 246	
Project website address: <i>under construction</i>		E-mail: p.traina@inrim.it	
Chief Stakeholder Organisation: CEN/CENELEC JTC- 22, WG2 Quantum Metrology		Chief Stakeholder Contact: Oskar van Deventer	
Internal Beneficiaries: 1. INRIM, Italy 2. Aalto, Finland 3. CMI, Czechia 4. DFM, Denmark 5. Metrosert, Estonia 6. PTB, Germany	External Beneficiaries: 7. ENS Paris Saclay, France 8. SQ, Denmark 9. Thales, France 10. UNITO, Italy 11. UNL, Portugal	Unfunded Beneficiaries:	
Associated Partners: 12. HWU, United Kingdom			

Publishable Summary for 23NRM05 SensMonCT II

Advanced detail sensitivity monitoring by new concepts to improve the reliability of safety relevant products using industrial computed tomography

Overview

Currently, the detail sensitivity of Industrial Computed Tomography (iCT) systems is evaluated by human operators which is unreliable and costly. Therefore, there is a need to develop traceable measurement and monitoring methods for determining the detail sensitivity of iCT systems and its standardisation. This project aims to address this need through the development of a) novel traceable test gauges to be measured in iCT systems and b) the respective evaluation algorithms, which will increase the reliability of the measurements of iCT detail sensitivity. By developing automated detail sensitivity monitoring for iCT systems, the project will provide the necessary metrological reliability of iCT in industry, including the automotive and aerospace sectors, and help to improve the safety of their products. Further to this, the project's results will be disseminated to relevant standard organisations, e.g. CEN/TC 138 and ISO/TC 135, in order to support their uptake and incorporation into standards at the earliest opportunity.

Need

iCT is a scanning technology with growing use in different sectors e.g. the automotive and aerospace industries. The conversion to electromobility in the automotive industry requires quality surveillance during the production of batteries and electrical engines, which is vital for public safety. The most reliable and holistic non-destructive inspection technique is iCT, which is currently applied in-line or at-line in serial inspections. Such iCT systems need to provide a stable performance, and therefore need to be regularly validated for example by using multi-scale gauges (millimetre down to sub-micrometre sizes).

In the aerospace industry, the use of additive manufacturing methods is increasingly offering significant benefits in production, especially for small series of parts. However, there is a need to develop more efficient and quieter aircrafts, whilst not compromising on public safety. To support this traceable and reliable iCT systems are needed. For these and similar industries, iCT detail sensitivity also needs to be verified before and after each inspection shift.

Due to their unique ability to image the entire volume including the inside of components, iCT systems are also increasingly used in Industry 4.0 for non-destructive testing (NDT) and dimensional metrology, and here their performance again depends on their detail sensitivity. Currently, industrially applicable gauges and automated analysis software are needed to measure the combined effect. Thus, new, and improved software for automated measurement of iCT detail sensitivity is needed to support this.

iCT is invaluable for quality assurance in safety-critical high-value manufacturing lines, including automotive, energy and aerospace manufacturing. However, to meet current and future requirements for product quality and safety, traceable methods to determine the detail sensitivity of iCT systems is needed together with an internationally recognised standard (Objectives 3 and 5). Indeed, standardising and automating the detail sensitivity measurement and monitoring process for iCT was identified as a priority need by CEN/TC 138 through the CEN/CENELEC/STAIR consultation, and this need was also published in ISO/TC 135/SC5, N508: Resolution 10/2023.

Report Status:
PU – Public, fully open

Publishable Summary

Issued: July 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



Co-funded by
the European Union

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Objectives

The overall objective of the project is to develop a traceable and repeatable measurement method for the automated measurement and monitoring of detail sensitivity of iCT systems and to provide a related draft standard. The specific project objectives are:

1. To develop accurate and traceable multi-scale gauges with features from a few millimetres down to sub-micrometre sizes, and (i) associated measurement algorithms, (ii) automated evaluation procedures and (iii) advanced monitoring of the digital detail detection sensitivity. To use computer-based modelling (i.e. digital twins) and consider radiation processes and a variety of iCT reconstruction algorithms.
2. To manufacture prototypes of the multi-scale gauges from Objective 1 and verify their use for evaluation procedures in iCT, including the determination of detectability limits and evaluation of their accuracy. To determine the optimal manufacturing technology for each of the different feature sizes of the gauges. To develop advanced evaluation methods based on the analysis of noise and resolution performance (spatial and contrast resolution).
3. Using the developments from Objectives 1 and 2, to traceably measure the features of the multi-scale gauges from a few millimetres down to sub-micrometre sizes including the selection and application of the most suitable metrological method for the gauge characterisation.
4. To develop freely accessible reference software, based on the algorithms from Objective 1, for the analysis of detectability limits for detail sensitivity for medium- and small-sized defects. In addition, to develop software based on automated digital algorithms, which includes long-term detail sensitivity evaluation, for quality assurance in iCT. Then to validate the developments from Objectives 1-4 in Round Robin tests.
5. To contribute to the standards development work of the technical committees CEN/TC 138/WG1 and ISO/TC 135/SC5 to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who will use them, and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Development of traceably measurable multi-scale gauges and automated evaluation algorithms

The detail sensitivity monitoring of iCT systems is currently based on the use of reference objects, so called representative quality indicators (RQI, ASTM E 1817), which are specifically manufactured and contain natural flaws or artificial defects of different shapes and sizes. A trained operator acquires an iCT data set with a defined geometrical setup and pre-set exposure data and evaluates the visibility of the relevant flaws in the iCT slice images. This is performed before and after testing and evaluating each object in a certain production series. Typically, this is done at the beginning and end of each shift in production. Because a human operator carries out the tests manually, the process is time-consuming, and the results depend on the tester capabilities, and the reproducibility is limited.

The EMPIR project 17IND08 AdvanCT focused on dimensional measurements, and produced several gauge designs suitable for use in iCT systems. However, the goal of 17IND08 was to establish measurement uncertainty for results of dimensional measurements, and therefore the gauge designs were not suitable for the determination of minimum size of defects / flaws. The EMPIR project 18NRM07 NanoXSpot also investigated gauges for iCT systems, but the project was restricted to the measurement of focal spots. This project will go beyond the state of the art by developing the first automated and traceable digital evaluation method for the detail sensitivity of iCT systems and multi-scale gauges with features from few millimetres down to sub-micrometre sizes. New gauges from different materials, different shapes and sizes will be designed, tested by X-ray simulation considering classical and modern iterative reconstruction algorithms. Corresponding simulation capabilities will also be developed for the gauges specific application(s). Further to this, a new automated algorithm will be developed based on the combination of the spatial frequency analysis of contrast and Modulation Transfer Function (MTF) combined with the theory of the detective quantum efficiency.

Manufacturing of prototypes of multi-scale gauges

Existing test gauges for the determination of the spatial resolution of iCT systems are available from the Japan Inspection Instruments Manufacturers' Association (JIMA-RT CT-01) with structures between 3 μm and 7 μm and the company QRM GmbH, which manufactures image quality indicators (IQIs), as phantoms for μCT .

However, whilst these are suitable to determine square wave MTFs, they cannot be used to determine sine wave MTFs as required in ASTM E 1695. The test gauges are also only available in the range of 1 μm to a few mm, which is not adequate to provide sensitivity monitoring for multi scale applications related to manufacturers specifications.

In this project, the new state of the art test gauges developed in Objective 1 for sensitivity monitoring and with traceable measurement features will be manufactured using modern subtractive and additive manufacturing as well as lithography and its combination. The test gauges will be manufactured in different scales to cover a large range of applications (e.g. electronics (μm), casting (mm), small and large assemblies (cm) and their manufacturing technology will be optimised. In addition, the gauges will be measured and evaluated for their functionality with the new advanced automated digital evaluation algorithms (Objective 1), based on spatial-spectral noise frequency analysis predicting the visibility of details.

Traceable measurement methods to characterise the multi-scaled gauges

The currently available line pattern gauges with structures in the μm range can only be characterised using scanning electron microscope (SEM) on the surface of filled structures. Thus, the subsurface geometry, and the cross section of the attenuating structures, is not characterised. Any deviation from the nominal cross section results in systematic measurement errors when using such gauges, and such deviations are known to occur in practice for the available resolution test gauges.

The state of the art gauges developed in this project will be suitable for quantitative measurement of the detail sensitivity if their features can be traceably measured. Hence, new traceable methods for the measurement of mm and sub- μm -scale features of the new gauges will be developed. Reference methods for determination of manufacturing accuracy (bias) and tolerances (precision) will also be developed for the new gauges.

Development of the evaluation software, reference images and Round Robin Test

Currently, Volume Graphics (part of Hexagon) and Waygate Technologies provides software which allows the determination of MTF, CDF (contrast discrimination function) and CDD (contrast detail diagram) separately for iCT applications. This is basic for the evaluation of the iCT detail sensitivity. The test gauge is a rod, defined in ASTM E 1695. However, this ASTM standard does not define the measurement procedure for CDD. In addition, the aforementioned measurement tools are not integrated into a single software tool for detail sensitivity determination. Thus, the measurement results based on the available software tools do not correlate well with the detail sensitivity determined by human observers.

The new validated reference software to be developed in this project will permit for the first time an automated analysis of the minimum size of detectable flaw or defect, based on the newly developed algorithm. The results will be tested in reference to the available analysis tools mentioned above. Reference images from simulation and measurements will also be made freely available to permit other software manufacturers to verify their developments and to validate their conformity to current standards. The software, the algorithm for the standard practice and the multi scale gauges, as well as their performance related to the detail sensitivity of human observers (current practice), will be evaluated within a Round Robin Test between project participants and, where possible, with project collaborators/stakeholders. Based on the results of the Round Robin Test, uncertainty budgets will then be determined.

New standard proposal to be developed in CEN/TC 138/WG1 and ISO/TC 135/SC5

ASTM issued the revised standards ASTM E 1441 and ASTM E 1695 describing the concept of CDD, which is not well understood for most users in industry, since it does not provide visibility (sizing) information of different flaw or defect types. In addition, four standard parts on Computed Tomography are considered in the working programme of ISO/TC 135/SC5, while no standards are available in CEN and ISO that permit the detail sensitivity monitoring of iCT systems.

In this project, measurement procedures and numeric algorithms will be developed, and recommendations will be provided for the development of a new work item proposal (NWIP) for EN ISO 15708-5 "Radiation methods for CT - Performance Evaluation and Long-Term Stability". The need for this has been highlighted by the resolution N508: "Resolution 10/2023, published by ISO/TC 135/SC5 in 2023, in liaison with CEN/TC 138/WG1.

Outcomes and impact

The consortium will actively reach out to stakeholders, such as iCT manufacturers and user groups. A project website will be created containing information actively on the progress of the project, as well as links to presentations, reports and papers from the project.

Outcomes for industrial and other user communities

The key results of the project will be new types of gauges which can be metrologically characterised, and new standardised analysis methods, as well as free software. These results are expected to be used by a broad range of users, including manufacturers of iCT systems, inspection and metrology service providers, and their respective customers for non-destructive quality examination in production lines e.g. in the fields of electronics, investment castings and additive manufacturing. The comparable and fair selection of iCT systems, based on accurate detail sensitivity measurements will also improve the ability of iCT in areas such as car and aerospace manufacturing, including electronic devices, electronic components like surface-mounted devices (SMDs), ball grids, packages of integrated structures, semiconductor packaging, batteries and fuel cells, new materials (e.g. metals, plastics, carbon fibre reinforced polymers (CFRP)), investment castings and medical components.

National and international manufacturers and users will be informed on the content and status of development during national and international conferences, as well as at stakeholder workshops, in order to increase their awareness of these methods and facilitate uptake. The project plans 2 workshops for the stakeholder community; (i) the first will be held at the beginning of the project (ii) and the second/ final workshop will be held at the end of the project so that it can present the results achieved by the project and allow time for discussion of the results with participating stakeholders. The second workshop will also incorporate a training course on the new methods and techniques developed in the project for sensitivity monitoring of iCT systems. The workshops will be open to European NMIs and DIs that are not part of the consortium, accredited laboratories and iCT manufacturers and users. The project will also involve industrial and other user communities through its Stakeholder Committee, invited participation in the Round Robin tests, e-newsletters and a project flyer, the latter will be published on the project's website and distributed to stakeholders.

The project's production of traceably measured test gauges and evaluation methods will enable reliable monitoring of inspection quality of iCT systems and will consequently (i) support an increase in the technical safety of products, (ii) allow the development of reliable new manufacturing processes and (iii) ultimately, the development of more energy efficient technologies. The transformation from evaluation of reference quality indicators by human operators to fully automated digital evaluation of traceably measured gauges is also needed for the integration of iCT measurements and its quality monitoring into production lines and to provide the related information to digital twins.

Outcomes for the metrology and scientific communities

The outcomes from this project will create early impact on the metrological and scientific communities by providing traceable measurement services for reference gauges and metrology for measurements of the long-term stability of iCT scanners. The project outcomes will support an increase in the credibility of iCT measurements and help to significantly improve identifying different types of defects and measuring their dimensions for the evaluation of acceptance/rejection criteria. One of the most important outcomes will be the availability of software tools that will determine minimum detectable defect or flaw sizes. The project's iCT evaluation software will be made available online as free software. To support this, the project will also provide access via Zenodo to a database of reference images and the results data from the evaluation software, including a manual. The database will be in an open format and will be ready to use by manufacturers and users of iCT systems software and users.

All these outputs will support NMIs to offer metrological quantitative CT measurements to industry and other users. In particular, participants VTT, METAS, FSB, PTB, LNE, CMI and RISE will be able to introduce calibration services for the measurement of the gauges, based on optical and tactile measurement methods, and iCT equipment developed by the project.

The project's scientific results will be published in peer reviewed journals, as well as in conference presentations and posters. In addition, the project will disseminate its outputs to the metrology and scientific communities through the EMN for Advanced Manufacturing and EURAMET's Technical Committee for length (TC-L).

The uptake of the results from this project will also create early impact on the metrological and scientific communities by providing traceable measurement services for test gauges and metrology for iCT system detail sensitivity monitoring. The project results will contribute to a significant increase in credibility of iCT systems, identifying different types of defects and measuring their dimensions. The developed measurement methods can be used also for other samples with similar structures.

Outcomes for relevant standards

The project will provide new measurement methods for a new draft standard, to be proposed for the standard series of EN ISO 15708 Non-destructive testing. It is intended that this draft standard will consist of the gauge requirements and a traceable measurement method for the detail sensitivity of iCT systems. In addition, it is hoped that the new draft standard can be the basis for further new standard developments at ISO/TC 135/SC5 (Ionizing radiation testing), ASTM E07.01 (Radiology method) and ISO/TC 213 (Dimensional and geometrical product specifications and verification). Indeed ISO/TC 135/SC5 has already proposed a related preliminary work item in document N508.

Further to this, the project will provide input to DGZfP is the German Society for Non-Destructive Testing, VDI/VDE-GMA technical committee 4.33 which deals with CT in dimensional measurement and BIPM Consultative Committee of Length (CCL), CIPM Working groups.

Longer-term economic, social and environmental impacts

Achieving net zero transport systems of the future requires the development of more sustainable manufacturing processes, the reduced use of raw materials, as well as a reduction in system weight to decrease overall transport energy demands. This needs to be coupled with the conversion to electromobility, green hydrogen technologies or carbon neutral fuels. To achieve all this, it is essential to develop new technologies whilst ensuring high safety requirements and minimal health and safety risks such as traffic accidents and battery or fuel system leaks. The most reliable and holistic non-destructive inspection technique to support these new techniques is iCT, but a precondition for iCT use is the assurance of traceable and stable performance of the iCT systems (which will be provided based on the outputs from this project).

The long-term competitiveness of the European iCT system manufacturing industry will be supported by this project's outputs through the development of a new draft standard for iCT use. The standard, when implemented in will support fair trade via better options for product comparison (CT scanners).

Future modern production of industrial goods in Industry 4.0 will be enhanced by digitisation, AI and networking. However, iCT systems need to be connected with these networks and the internal software must be able to monitor the system properties e.g. the iCT system detail sensitivity. The application of high-resolution metrological iCT systems will help to enable the quality assurance and optimisation of new designs and more efficient manufacturing processes, which will help to reduce energy consumption and hence reduce pollutants. Thus, this project will support and help to optimise Industry 4.0 production lines for modern electrical cars and high-precision fuel injection systems and modern catalytic converters, which are also used in marine, power generation and locomotives. Other sectors such as the semiconductor, micro-technology, aviation, energy, and pharma-biotech will also benefit from the project's outcomes.

List of publications

n/a

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		01 July 2024, 36 months	
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Project website address: n/a			
Chief Stakeholder Organisation: Baker Hughes Digital Solutions GmbH		Chief Stakeholder Contact: Dr. Eberhard Neuser	
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:	
1. FSB, Croatia	7. DTU, Denmark	11. Comet Yxlon, Germany	
2. CMI, Czechia	8. FAU, Germany	12. Hexagon, Germany	
3. LNE, France	9. KOWOTEST, Germany	13. Safran, France	
4. PTB, Germany	10. microworks, Germany	14. VisiConsult, Germany	
5. RISE, Sweden			
6. VTT, Finland			
Associated Partners:			
15. METAS, Switzerland			
16. UoS, United Kingdom			

Publishable Summary for 23RPT01 WAC Wideband AC quantum traceability

Overview

A “practical” traceability route for AC measurements based on thermal converters relating AC values to DC values has been established at NMIs and DIs for many decades, however this is limited to RMS (Root Mean Square) values only and requires long measurement times. The new SI realisation of the ampere based on quantum standards allows direct traceability for AC measurements. New techniques and tools for the digitalisation of the traceability chain for AC electrical quantities have been developed in a series of EMRP and EMPIR projects. However, these must be further improved to establish the link between quantum standards and calibrations with a broader frequency and amplitude range for widespread implementation. This project will implement quantum techniques for AC measurement voltage for the increased bandwidth up to 100 kHz and amplitude to 10 V with a target uncertainty of 10 $\mu\text{V/V}$ by utilising a sub-sampling differential method, will develop three working implementations of a wideband quantum voltmeter standard which will be validated via a comparison, plus algorithms and software. This will reduce the uncertainties of AC voltage measurement, speed up calibration services, and provide the ability to switch from RMS voltage to measuring real harmonic components. The project will also create a comprehensive description and documentation of the new methods and standards, enabling efficient uptake of the new capabilities especially by less experienced NMIs and DIs.

Need

Metrology in the audio range and frequencies up to 100 kHz has the largest impact on the electronic component industry, the power quality industry, and sensors of physical quantities. The existing metrological chain for AC voltage from 1 kHz up to 100 kHz relies on thermal transfer standards, which are reliable but time-consuming. Furthermore, thermal converters only provide accurate information about the RMS value of a signal and cannot give information about the harmonic content of waveforms. The calibration of spectral components therefore relies on simulation of standard resistors, calculable impedance standards, or digitizer properties. The new SI realisation of the ampere based on quantum standards allows direct traceability for low frequency AC measurements, but this direct link is missing in most NMIs/DIs or burdened by many calibration steps. In addition, the increasing importance of dynamic and multi-tone signals, particularly in digital to analogue converters, necessitates a new traceability link to quantum standards.

The number of European quantum voltage standards has increased due to technological advancements and research and knowledge dissemination projects supported by EURAMET, EMRP, and EMPIR, and this has led to a rise in calibration laboratories operating a Programmable Josephson Voltage Standard (PJVS), such as DC Josephson Voltage Systems. However, turning a PJVS into an AC quantum voltmeter is complex and the bandwidth is currently still limited to 1 kHz, and to make use of the sub-sampling method for increasing the bandwidth to 100 kHz is even more difficult. An individual NMI cannot complete the whole development and validation process including algorithms and software, and it requires infrastructure for validated wideband AC quantum standards and a collaboration between many NMIs. To enable this quantum-based technology to be adopted beyond a few very experienced NMIs and institutes and across a wider range of organisations, effective knowledge transfer between organisations is required, together with an increase in the capabilities of less developed institutes.

The power industry, the largest economic sector in electrical metrology, is investing heavily in renewable energy facilities to reduce greenhouse gas emissions. As the European electrical grid becomes interconnected

Report Status:
PU – Public, fully open

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European Partnership



Co-funded by
the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY
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Issued: July 2024

with new countries such as Estonia, Latvia, Lithuania, and Ukraine, the need for improved transmission and distribution grid technology increases. Power quality is decreasing, and increasing monitoring precision and reliability is crucial to avoid blackouts. Existing quantum standards are usable up to 1 kHz, while the bandwidth of interest for power quality goes up to 75 kHz. Only the latest quantum technology can reduce the uncertainties and meet the new needs.

Industry 4.0 is based on factory automation, and this means it also needs to be supported by appropriate calibration methods. Current calibrations based on thermal standards still rely on manual operation. By increasing the bandwidth of quantum standards up to 100 kHz, one standard will be capable of multiple tasks, increasing the value of existing and newly installed quantum standards.

Objectives

The overall objective of the project is to implement quantum techniques for measurement of AC voltage in the increased bandwidth up to 100 kHz and amplitude to 10 V, and to transfer knowledge by sharing information and using open-source software.

The specific objectives of the project are:

1. To **develop methods, techniques, algorithms, and control software** for calibration of AC voltage sources and measurement instruments at frequencies up to **100 kHz** and 7 V RMS amplitude with an uncertainty better than 10 $\mu\text{V/V}$ by utilising **sub-sampling** and differential sampling and by expanding on the methods, algorithms, and software developed in previous EMRP and EMPIR projects.
2. To develop **three working implementations** of the expanded open quantum sampling standard working up to the increased bandwidth and specified voltages based on existing commercial devices.
3. To **transfer the expertise** in AC Josephson standards to emerging NMIs through the exchange of knowledge and know-how, and to develop a coordinated approach for the replacement of AC traceability from thermal transfer techniques to Josephson standards in the increased bandwidth.
4. To facilitate the take-up and **long-term operation** of the methods, techniques, know-how, and measurement infrastructure for AC measurements developed in the project by the measurement supply chain (NMIs and DIs, calibration and testing laboratories, EMN-Q and EMN SEG), and **end users** (industry, instrument manufacturers).

Progress beyond the state of the art and results

Calibration of AC voltage sources in the frequency range up to 100 kHz

The new quantum wideband method developed in the project will offer quantum traceability for AC voltage in a frequency range up to 100 kHz and uncertainties below 10 $\mu\text{V/V}$, allowing a transition from thermal transfer, RMS metrology to quantum traceable metrology of multi-tone signals. This transition will improve uncertainties and will be applicable to new measurement devices such as power quality meters that require knowledge of signal components. The target is to reduce uncertainties within the increased frequency range by half compared to thermal transfer standards, resulting in lower calibration uncertainties for various types of meters and calibrators.

Implementations of a quantum AC voltage standards

The project's goal is to extend existing systems, without requiring expensive hardware, by delivering a new measurement method based on an expanded open quantum sampling standard for AC voltage. Three institutes will develop the systems and validate them in the scope of the project, and other institutes, ACL and industry are expected to follow up early. This will bring new capability to already-installed resources, substantially increase the value of investments, and improve the overall European metrology network.

Transfer of the expertise in AC Josephson standards to emerging NMIs and development of a coordinated approach for the replacement of AC traceability from thermal transfer techniques to Josephson standards

The project will deliver a description of the new wideband quantum system for AC voltage, as well as open-source data processing algorithms and control software, allowing all other project participants and interested parties to easily obtain the knowledge, know-how and to apply the results to their quantum

standards. A preliminary international comparison will be conducted to validate the newly developed systems. Therefore, it will be immediately ready to be implemented in other institutes and will accelerate the spread of the new system. Researchers from emerging institutes will travel to selected institutes to help build a system, ensuring genuine knowledge transfer, development of research skills, and experience in building wideband quantum setups. Collaboration between emerging and experienced NMIs will accelerate metrological and research capabilities.

Building capacity, and facilitating take-up and long-term operation of the methods, techniques, know-how, and measurement infrastructure for AC voltage measurements

For smaller NMIs, maintaining a vast number of calibration systems for AC voltage measurements presents a significant economic and staff resource burden. The project's goal is to build capability and capacity within the target NMIs/DIs by extending existing systems without requiring expensive hardware, by delivering a new measurement method for AC voltage measurements for existing devices. This will bring new capability to already-installed resources, substantially increase the value of investments, and improve the overall European metrology network. To build capacity and capability beyond the project participants, take up of the capability will be encouraged via the project's website, presentations and posters, papers, a workshop, liaison with technical committees, liaison with the metrological networks (in particularly EMN-Q and EMN SEG), and a series of training videos.

Outcomes and impact

Outcomes for industrial and other user communities

The wideband quantum measurement system developed in the project will reduce uncertainties in AC voltage calibrations over a frequency range of up to 100 kHz, and enable harmonics rather than just RMS values to be measured. This system will also enable lower uncertainties for calibrations of multimeters, power quality meters and others, enabling higher-value devices and better characterisation of metrology products. Lower uncertainties will support further development and upcoming research of measurement devices.

AC voltage meters and calibrators are used in the production of electronic components such as capacitors, inductors, and AC resistors, and reduced uncertainties will result in improved manufacturing processes. AC voltmeters, total harmonic distortion (THD) meters and power quality meters are crucial for assessing electric power quality. With the rise of small, distributed power plants such as photovoltaic solar panels and with the rise of electromobility, precise power quality measurement is an important factor in preventing blackouts and facilitating the transition to renewable energy sources. The improved precision of the new wideband quantum standard will ensure the ongoing improvements in this field.

The comprehensive description of the wideband quantum method, including a guide, connection schemes, uncertainty budgets, and tutorial videos, created in the project will facilitate the adoption of quantum standards for quantum traceability in the PJVS standard, thereby improving the use-to-cost ratio. The results of the project will be made available as open source, enabling easy integration of calibration routines into company procedures, thereby paving the way for automated systems, crucial for Industry 4.0.

Outcomes for the metrology and scientific communities

The new quantum based differential sub-sampling method for AC voltage calibration, the 3 new wideband AC quantum voltmeter (WBQV) systems created in the project, and the knowledge gained, will significantly improve, and increase the capabilities for AC voltage measurement within both the less experienced and more experienced NMIs and DIs in this field. The project will take another step toward removing old thermal techniques by increasing the bandwidth of the quantum voltmeter, just as AC quantum voltmeters (ACQVM) did with thermal techniques in frequencies up to 1 kHz. The transition to quantum-based standards for AC voltage will enable measurements to be performed much faster than at present and multi-tone signals to be traceably calibrated.

The project will create a detailed description and documentation of the new wideband quantum system and differential sub-sampling quantum method, including a guide, connection schemes, uncertainty budgets, and tutorial videos. This will ensure fast adoption, replication, and rapid transition to quantum methods. The method description and the comparison protocols developed in the project will also serve as a foundation for comparisons planned by international and European electricity-related committees.

The algorithms and control software will be released as open-source code that will avoid the development of similar software in multiple labs, shorten adoption time, and save money and staff time. The algorithms included in the software will provide a necessary foundation for evaluating the results, which is essential for calibration, validation, comparison, and standardisation. The project's expertise in uncertainty estimation will help the establishment of new uncertainties for NMIs and accredited calibration laboratories, ensuring a smooth introduction of new CMCs after the end of the project. This will decrease the calibration uncertainty for traceable devices such as multimeters, calibrators and power quality meters, impacting the instrumentation industry and power sector. The validation of the measurement method, data processing algorithms, and software will facilitate the adoption of quantum measurement by less developed NMIs or accredited calibration laboratories, leading to faster standardisation and reduced uncertainties in metrology and industry.

The project's key component is the knowledge transfer, which will ensure swift implementation of new quantum standard across multiple institutes and increased capabilities of less developed institutes.

Outcomes for relevant standards

The participants will disseminate information on the project's progress and results (especially documentation on methods, algorithms, and software) to international and European electromagnetic metrology committees, such as CIPM CCEM and EURAMET TC-EM, and to other international technical committees such as IMEKO TC4. The extension of the new measurement method for AC voltage up to 100 kHz will serve as a basis for a future new key comparison for AC voltage in the scope of CCEM-WGLF. Once the AC/DC voltage thermal transfer voltage measurement is replaced by more accurate quantum-based methods, the CCEM-WGLF may decide at some point in the future to substitute AC/DC voltage for AC quantum voltage on the list of key quantities.

Moreover, the results of the project will be presented to BIPM, which maintains the travelling quantum standard for DC voltage (to offer bilateral comparison with the lowest possible uncertainty). BIPM may then decide to implement the new measurement method and extend the comparison scope to wideband AC voltage based on quantum standards.

The project's results will be presented to relevant legal metrology and standardisation organisations, including IEC, CENELEC and WELMEC, as this will allow the project outputs to be taken into account in future normative documents.

Longer-term economic, social and environmental impacts

The project will contribute significantly to the creation of a coordinated European electrical metrology infrastructure. Extending advanced technologies to more European NMIs/DIs and calibration laboratories will broaden the applicability of existing quantum standards, and hence increase the economic cost benefit ratio of purchasing an expensive quantum standard. This will lead to improved traceability links for AC voltage and power quality, reducing uncertainties and affecting the entire electronic component and power quality industry, resulting in improved distribution grids and grid stability.

Improved traceability and equipment testing will strengthen the electronics industry and electricity distribution by providing more reliable measurements with lower calibration uncertainties. This will boost competitiveness and confidence in power measurements in European countries, crucial for the goal of 100 % renewable energy generation. More reliable monitoring of the power quality from energy grids could help reduce poor power quality and the chance of blackouts.

Quantum traceability for AC voltage measurement will significantly impact sensors and power measurement. Sensors for various physical quantities such as strain, force, and chemical activity rely on AC voltage measurement, and lower uncertainties for calibrations will lead to better environmental assessment. With the rapid growth of electric vehicles in Europe, improved measurements for electrical power at charging stations are crucial for a fair electricity market, and this project will contribute to increasing electrical power measurement capabilities across Europe through simplified traceability for calibration services.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months
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E-mail: msira@cmi.cz		
Project website address: -		
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CMI, Czechia	8. INTI, Argentina	-
2. CEM, Spain	9. LeftRight, Slovenia	
3. FER, Croatia	10. Supracon, Germany	
4. INRIM, Italy	11. SUT, country	
5. JV, Norway	12. UNICA, Italy	
6. PTB, Germany		
7. TUBITAK, Türkiye		



Publishable Summary for 23RPT02 ETraceAbs Establishing European traceability for medical measuring devices through optical absorbance liquid filters

Overview

All medical measuring devices (MMDs) need to be verified to comply with the EU's Medical Devices Regulation (2017/746) and standards. Many devices, such as those used in clinical diagnostics, use optical absorbance as the measurand. Optical absorbance liquid filters (OALF) are used to calibrate optical absorbance equipment, but there is currently a capability gap across NMIs and DIs in the manufacturing, characterisation, and use of such filters, which leads to a lack of traceability. This project aims to bridge this gap by supporting the development of measurement capabilities for optical absorbance of liquid filters in emerging NMIs and DIs, and to enable them to provide traceability of measurement results as well as OALF as reference materials to national and international stakeholders with the lowest possible measurement uncertainty. This will improve the accuracy of clinical measurements and treatment outcomes for patients.

Need

More accurate diagnostics are needed to improve clinical outcomes thereby decreasing mortality rates, reducing healthcare costs and improving quality of life of citizens. As well as improving healthcare systems, it is also important to ensure that public trust and confidence in European medical institutions is maintained.

Many MMDs (e.g., ultraviolet-visible (UV-VIS) spectrophotometers), measure optical absorbance in micro volumes. The devices must be calibrated for absorbance according to pharmaceutical quality standards (detailed in European Pharmacopeia), but some instruments should also be calibrated for absorbance at required specific wavelengths due to their construction. However, precise calibration methods of absorbance at required wavelengths are not usually possible using commercially available liquid and solid traceable standards. Therefore, criteria for appropriate materials as reference OALF are needed.

Accredited calibration laboratories, inspection bodies and MMD manufacturers need to deliver quality medical and metrology services, and as a result NMIs need to provide optical absorbance measurement results traceable to SI units. OALF, in addition to other reference materials for MMDs, can be used to achieve this but further work is needed. Specifically, organisations which perform calibration, verification, inspection, and conformity assessment of MMDs need the availability of national capabilities for traceable measurements of absorbance of OALF for the spectral range of 220 nm to 780 nm, and for the photometric range up to 3.000 absorbance to adequately assess and to ensure the reliability of the measurements of MMDs.

In addition, in order to ensure that the optical absorbance measurement results provided by NMIs and DIs to end users follow internationally accepted standards, measurement intercomparisons and skills testing need to be performed to establish equivalence across Europe. Most of the participant NMIs need this as formal evidence of the quality of their absorbance measurements for providing calibration services to testing laboratories, medical bodies, and inspection bodies in their countries.

The EU Regulation 2017/746 includes requirements for “Devices with a measuring function”, but there is no clear division and description of the requirements. Concomitantly, according to the ISO 15189:2012 standard, all MMDs with high impact on measurement results must be calibrated. For spectrophotometers, general characteristics and methods of testing and verification are specified in OIML standard R135 however

Report Status:
PU – Public, fully open

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

European Partnership  Co-funded by the European Union

Publishable Summary

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Issued: June 2024



references are outdated, and it does not provide procedures that can be fully adopted for MMDs. Recommendations and a good practice guide are needed on the manufacture, characterisation, and use of OALF to revise these outdated OIML standards.

Objectives

The overall objective for this project is for emerging NMIs (BIM, CMI, DMDM, INM, INRIM, IPQ, TUBITAK and UMTS) to develop and for established NMIs/DIs (Aalto, GUM, RISE, and SMU) to upgrade their national metrological capacity in SI-traceable measurements of optical absorbance of liquid absorbance filters.

The specific objectives of the project are:

1. To determine a set of minimal criteria (physical and chemical properties) for optical absorbance liquid filters as reference materials, which will include a dilution series of optical absorbance liquid filters to be characterised and calibrated.
2. To develop traceable measurement capabilities of absorbance of optical absorbance liquid filters in emerging NMIs and DIs for the minimum spectral range from 220 nm to 780 nm, and absorbance range from 0.001 up to 3.000 (corresponding to a nominal internal transmittance of 99.77 % and 0.1 %, respectively), at atmospheric pressure, within the temperature interval from 15 °C to 40 °C and with a relative standard uncertainty of 0.3 % to 1.0 %.
3. To establish equivalence in the measurement of optical absorbance liquid filters across participating European NMIs according to capabilities developed in Objective 2.
4. To produce a good practice guide on the manufacture, characterisation, and use of optical absorbance liquid filters, which will be shared with EURAMET TC-PR along with a request for its consideration to be published as a EURAMET guide.
5. To facilitate the take up and long-term operation of the capabilities, technology and measurement infrastructure for optical absorbance measurements using optical absorbance liquid filters developed in the project, by the measurement supply chain (NMIs/DIs, calibration, and testing laboratories), standards developing organisations (OIML, EURAMET TC-PR), and end users (e.g., industry, instrument manufacturers, regulators). To include preparation of strategies and roadmaps for the future development of these capabilities by all participant NMIs.

Progress beyond the state of the art and results

Determination of minimal criteria for optical absorbance liquid filters as reference materials

Currently, precise calibration methods of MMDs for absorbance at required specific wavelengths are not possible using commercially available liquid and solid traceable standards and the calibrations are performed at approximate wavelengths and absorbance levels. The project will set criteria for appropriate materials as reference OALF and propose several types of OALF covering the optical absorbance from 0.001 to 3.000 in the spectral range from 220 nm to 780 nm according to available knowledge and review of the existing literature. The new reference and traceable OALF developed in the project will help to improve the limited range of commercially available standards.

Traceable measurement capabilities of absorbance of optical absorbance liquid filters in emerging NMIs and DIs

Almost all NMIs/DIs from Europe have recognised optical absorption measurement capabilities, but the problem is that not all of them have the necessary experience in the manufacturing, characterisation and use of OALF and the use of these liquid filters in ensuring traceability of MMDs. The project will establish traceable measurement capabilities in OALF by developing new measurement systems or by improving the existing facilities in emerging NMIs/DIs. This will allow the dissemination of optical absorbance via future Certified Reference Materials (CRMs), targeting a low uncertainty of 0.010 at an absorbance level of 3.000 and at temperatures between 15 °C and 40 °C, to be used for the dissemination of the unit of optical absorbance to national healthcare services, medical laboratories, and testing laboratories.



Establishment of equivalence in the measurement of optical absorbance liquid filters

At present, most of the participant NMIs do not have formal evidence of the quality of their optical absorbance measurements of OALF and cannot provide calibration services to testing laboratories, medical bodies, and inspection bodies in their countries. The project will allow all participants to participate in measurement intercomparisons to validate their development efforts. The NMIs/DIs will be able to establish a complete national traceability chain at a level of uncertainty close to the expert institutes for the MMDs.

Good practice guide on the manufacture, characterisation and use of optical absorbance liquid filters

The instructions and guidance available from different standards developing organisations are not fully relevant to the sophistication and precision level of present instrumentation and lack details on technological progress of MMDs. With support of the EURAMET TC-PR, the project will develop a good practice guide on the manufacture, characterisation and use of OALF, and will request EURAMET to consider its publication as a EURAMET guide. Targeting the end-users, the good practice guide will include chapters for medical laboratories, manufacturers of MMDs, testing laboratories, inspection bodies and calibration laboratories concerning the correct selection and use of OALF nominated as CRMs.

Outcomes and impact

Outcomes for industrial and other user communities

The new measurement systems for the OALF and production of reference standards developed in the project will enable accredited bodies and calibration and measurement laboratories to implement a recognised traceability chain for OALF measurements which are used for calibration, inspection and verification of MMDs. This will lead to new national accreditation schemes.

The reference materials developed in the project will ensure that testing laboratories and medical laboratories can link the optical absorbance quantity for their MMDs (e.g., biochemical and immunological analysers) to SI units. This will enable them to ensure the reliability of their measurements.

To encourage the uptake of results, the project will organise at least two workshops for the end-user community (i.e. accredited laboratories, research centres, technical assessors for accreditation bodies, etc.) to disseminate best practices in ensuring metrological traceability for MMDs by using OALF.

Outcomes for the metrology and scientific communities

The development of capabilities for SI traceable measurements of optical absorbance using OALF developed in the project will enable emerging NMIs/DIs to establish a complete national traceability chain at a level of uncertainty close to the expert institutes for the MMDs, with the potential for recognition and demonstration of competence in accordance with CIPM MRA. This will address the lack of European Calibration and Measurement Capabilities (CMCs) in the BIPM database regarding optical absorbance measurements, as well the lack of CMCs for CRM for optical absorbance. The metrology and scientific communities will benefit from improved global equivalence and reduced uncertainty in key metrological areas such as spectral transmittance and absorbance.

Outcomes for relevant standards

The good practice guide on the manufacture, characterisation, and use of OALF with application for MMDs will contribute to the revision of outdated International Organisation of Legal Metrology (OIML) standards regarding the use of spectrophotometers for medical laboratories (OIML R 135). The good practice guide will also be submitted to EURAMET TC-PR for publication as a EURAMET guide.

The consortium will also share results of the project with other relevant standards bodies including CIE (TC2-98, related to the measurement of reflectance and transmittance), CCPR (whose activities concern measurement standards for photometric and radiometric quantities and development of absolute radiometry), and ISO (TC 172, optics and photonics).

Longer-term economic, social and environmental impacts

This project will support accredited bodies, national healthcare services and the research community through the implementation of recognised traceability chains for MMD measurement. This project will significantly advance the expertise on manufacturing, characterisation and use of OALF, in less experienced NMIs, for



ensuring traceability of MMDs. This will lead to improved quality of diagnostics and cost efficiency in the healthcare system. The build-up of measuring capabilities will empower emerging NMIs/DIs to offer extended and improved calibration services and CRMs, fulfilling the needs of the national services and healthcare institutions. An important aspect is to provide the means for fulfilling the legal metrological aspects for MMDs. It has huge healthcare impact for the EU internal market and provides the basis for the implementation of necessary measures for public protection. The resultant impact of the project will lead to an increase in the protection of European citizens by increasing the confidence level in measurements of MMDs. Smart specialisation of European NMIs through realisation and implementation of an improved spectral transmittance-absorbance scale will provide better traceability to light based diagnostic instruments used at the point of care. Finally, the project will improve the capabilities of European NMI/DIs in the measurement of spectral absorbance of substances. This will have a positive impact on getting more accurate and reliable results from the tests performed for water quality monitoring and environmental protection.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 Months
Coordinator: Farshid Manoocheri, Aalto		Tel: +358505902483
Project website address: -		E-mail: farshid.manoocheri@aalto.fi
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. Aalto, Finland	10. BIM, Bulgaria	-
2. CMI, Czechia	11. DMDM, Serbia	
3. GUM, Poland	12. INM, Moldova, Republic of	
4. INRIM, Italy	13. UMTS, Ukraine	
5. IPQ, Portugal		
6. PTB, Germany		
7. RISE, Sweden		
8. SMU, Slovakia		
9. TUBITAK, Türkiye		
Associated Partners: 14. AGILENT UK, United Kingdom		

Publishable Summary for 23RPT03 GrainMet

Metrology for standardised moisture / water content measurements in plant-origin bulk materials in support of International and European food safety and trade

Overview

Determination of the water content in plant-origin bulk materials is important for international and European food safety and trade. With data on the water content, the quality, storage conditions, price and safety of a material can be estimated. The water content in thousands of tons of cereals, wood pellets, straw and their refined products is determined daily in many industrial and scientific laboratories. However, KCDB supported CMCs, and the respective certified reference materials (CRMs), are not yet available for use in measuring the water content in plant-origin bulk material. Therefore, a Karl Fischer titration method for measuring the water content in plant-origin matrices and a certified reference material (CRM) candidate will be developed to provide traceability to the International System of Units (SI) and to support CMC claims.

Need

Reliable water / moisture measurements in plant-origin bulk materials, and most importantly in grains and cereal products, is a crucial need for quality assurance and risk reduction. Moisture affects stability during storage and transportation. Too much moisture can lead to spoilage, e.g., mould growth, which leads to wasted food and potentially to foodborne illnesses. Consequently, regulatory bodies set moisture content limits for specific products to ensure consumer safety and product quality. Accurate moisture measurement is needed to demonstrate compliance with the limits.

The currently used standard method for moisture measurement utilise mass loss on drying. However, with this method, it is not clear whether water alone, or other volatile substances are also evaporated. Therefore, a volumetric Karl-Fischer (vKF) titration method needs to be developed to selectively measure water in plant-origin bulk materials (Objective 1).

The loss on drying method also often lacks direct SI traceability. This is largely because this method is relative and depends on the specific characteristics of the material under test, which can vary widely. The vKF titration method needs to be developed to significantly enhance the reliability and precision of water determination (target uncertainty of ± 0.3 % absolute), which will benefit agriculture, food production, food storage and food safety. Importantly, the developed method will produce metrologically traceable results. To ensure that the developed vKF method is suitable for use it should undergo careful validation, using the best approach which is interlaboratory validation by interlaboratory comparison measurements (Objective 2).

Standardisation ensures consistency and comparability of results across different laboratories and industries. A plant-origin CRM candidate needs to be developed, which will significantly contribute to the metrology community by serving as a calibration standard that will enable laboratories to validate and calibrate their instruments accurately (Objective 3).

This project aims to ensure that all of its results are adopted and utilised effectively by various stakeholders, including established and emerging NMIs/DIs, calibration laboratories, industry, and regulators. Collaboration with EURAMET NMIs/DIs will ensure that measurement practices are consistent globally, facilitating trade and research cooperation (Objective 4).

Report Status:
PU – Public, fully open

Publishable Summary

Issued: July 2024

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership



Co-funded by the European Union

METROLOGY PARTNERSHIP





Objectives

The overall objective of this project is to develop methods, using vKF or cKF titration, for determining the water content in plant-origin bulk materials and to transfer this knowledge to the countries that need it (e.g., Georgia, Moldova, Ukraine, Austria).

The specific objectives of this project are:

1. To develop the vKF titration method for use in measuring the water content of plant-origin bulk materials. The standardised method should provide metrologically traceable measurements with target uncertainties of ± 0.3 % absolute. In addition, the accuracy and reliability of the method should be validated using commercially available CRM.
2. To organise and conduct a measurement comparison in order to establish the performance and limitations of the vKF titration method developed in objective 1 and the two CRMs prepared in objective 3. In addition, the reliability and robustness of the method should be validated by comparing the results with those obtained using the ISO 712 reference method and these CRMs should be validated, at international level, for use with automated KF titrators.
3. To develop at least one plant-origin matrix CRM representing the most commonly handled materials and one "grain simulant" CRM for water / moisture content, with guaranteed stability over a specified and determined timeframe which will provide traceability to the SI. The CRMs should have target relative uncertainties within the range of ± 1 % - ± 5 % and be suitable for use with the vKF titration method developed in objective 1. CRMs are intended to be used in the calibration of the instruments that are used to measure moisture in harvested and stored bulk materials of plant-origin.
4. To facilitate the take up and long-term operation of the capabilities, technology, and measurement infrastructure for standardised water / moisture content measurements in plant-origin bulk materials developed in the project, by the measurement supply chain (NMIs/DIs, calibration, and testing laboratories), and end users (e.g., industry, instrument manufacturers, regulators). The approach should be discussed within the consortium and with other EURAMET NMIs/DIs, e.g., via ISO TC34 and the EMN for Safe and Sustainable Food, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole. A EURAMET calibration and measurement guide should also be developed.

Progress beyond the state of the art and results

To develop the vKF titration method for use in measuring the water content of plant-origin bulk materials. The standardised method should provide metrologically traceable measurements with target uncertainties of ± 0.3 % absolute. In addition, the accuracy and reliability of the method should be validated using commercially available CRM. (objective 1)

A comprehensive review of existing water / moisture content measurement methods and protocols for plant-origin bulk materials will be conducted. Gaps and areas for improvement will be identified through a collaborative effort involving metrologists, researchers and industry experts. Leveraging this knowledge, standardised measurement protocols utilising the vKF titration method will be designed and validated. The protocols will consider the unique characteristics of different plant-origin materials to ensure accuracy and consistency in moisture content determination. The result of this work will be comprehensive standardised protocols for measuring moisture content in plant-origin bulk materials, tailored to different matrices and moisture ranges, as well as guidelines and documentation detailing the implementation of the standardised protocols.

To organise and conduct a measurement comparison in order to establish the performance and limitations of the vKF titration method developed in objective 1 and the two CRMs prepared in objective 3. In addition, the reliability and robustness of the method should be validated by comparing the results with those obtained using the ISO 712 reference method and these CRMs should be validated, at international level, for use with automated KF titrators. (objective 2)

Traceability links to the SI will be established for water content measurements. This will involve calibrating measurement instruments using the developed CRM candidates and standardised protocols, thus ensuring the traceability of water content measurements. The outcome of this work will be a traceability framework,



which will outline the procedures and methodologies for achieving traceability, of water content measurements, to the SI units. In addition, calibration guidelines will be prepared to enable metrologists and laboratories to maintain traceable moisture content measurements, fostering credibility and confidence in the metrological traceability of results.

To develop at least one plant-origin matrix CRM representing the most commonly handled materials and one "grain simulant" CRM for water / moisture content, with guaranteed stability over a specified and determined timeframe which will provide traceability to the SI. The CRMs should have target relative uncertainties within the range of $\pm 1\%$ - $\pm 5\%$ and be suitable for use with the vKF titration method developed in objective 1. CRMs are intended to be used in the calibration of the instruments that are used to measure moisture in harvested and stored bulk materials of plant-origin. (objective 3)

A wide range of plant-origin bulk materials will be characterised for their moisture content using the validated standardised measurement protocols. The collected data will facilitate the development of CRM candidates which will be representative of different plant-origin matrices and moisture levels. These CRM candidates will undergo rigorous validation and certification processes to ensure accuracy, stability and homogeneity. Plant-origin CRMs will serve as essential tools for calibrating and validating the measurement instruments and methods that are used by industry and scientific laboratories. At least one CRM candidate, with a known and traceable water / moisture content value and a comprehensive CRM documentation package, including a reference material certificate, a certification report with instructions for use, and recommended handling and storage guidelines will be prepared.

Outcomes and impact

Outcomes for industrial and other user communities

This project will impact many industries, particularly those involved in the storing, handling, processing and trade of plant-origin bulk materials as well as the metrology and science community, including the industrial unfunded beneficiary Nibulon from Ukraine. Further companies from Georgia (collaborator), Ukraine, Moldova and Europe will be involved in this project via its planned creating impact activities.

Accurate moisture content measurements, facilitated by standardised protocols and traceability to the SI units, help industries to better manage their raw materials and to reduce the over- or under-drying of plant-origin bulk materials. Utilising traceable measurements based on the SI units, and adhering to standardised protocols and reference materials, will assist industries in meeting regulatory requirements and in ensuring that their products meet the necessary safety and quality standards that are necessary for trade.

The results from this project, e.g., guidelines, recordings of the workshops (for use as e-training), will be disseminated via the project's public website in order to transfer the knowledge to calibration laboratories and industrial stakeholders in the field of moisture / water determination. At least one international workshop will be organised by the project for the measurement and traceability of water determination using vKF titration. The collaboration and knowledge transfer between the measurement supply chain and end users will foster a greater understanding and appreciation of the importance of standardised measurements in ensuring food safety and facilitating international trade. This will promote the uptake of best practices in measurement, raising overall standards in the industry.

Outcomes for the metrology and scientific communities

The outcomes of this project will significantly improve the accuracy and reliability of water / moisture measurements in plant-origin bulk materials. The increased accuracy and more firmly established traceability to the SI will reduce the risk of errors and, therefore the potential for costly recalls or quality issues. The creation of a plant-origin CRM candidate will provide a much-needed reference for calibration, thus further enhancing the reliability of moisture content measurements. This CRM candidate will be an indispensable tool for laboratories and industries worldwide, as it will ensure the consistency and comparability of their measurements. The method validation and performance comparison will contribute to the further refinement and optimisation of the vKF titration method, thereby also improving the measurement capabilities of the participants. It will provide valuable data for the scientific community, contributing to the body of knowledge in the fields of metrology and material science. The outcomes of this project will form a good basis for introducing water content measurement services on the basis of the developed vKF method, either by NMIs/DIs or by the analytical laboratory community.



The outcomes will be disseminated through workshops and web materials and these will be available for the metrology and scientific communities as well as for industrial stakeholders. In addition, the outcomes will be disseminated to the scientific community via publications.

Outcomes for relevant standards

Most of the work in determining food quality and safety at an industrial level is carried out according to standards. Thus, support for standardisation is a key outcome of the project. The outcomes of this project including information on the standardised method for the measurement of the moisture content in plant-origin bulk materials, as well as information on the corresponding CRM candidate, will be provided to standards development organisations for them to use as the basis for new or improved international and European standards. For instance, the International Organization for Standardization (ISO) has several relevant committees such as ISO/TC 34 - Food products, which draft and develop standards related to the food industry and the use of plant-based materials. The results from this project could significantly inform their work. If possible, the results from this project will be disseminated to ISO/TC 34/SC 4 to be considered for incorporation into new or existing standards (ISO 712-1, ISO 712-2, ISO 24557). Similarly, the European Committee for Standardisation (CEN) has technical committees such as CEN/TC 338 -- Cereals and cereal products, which could greatly benefit from the findings of this project.

Longer-term economic, social and environmental impacts

Overall the project's successful progression beyond the current state of the art and the resulting technical outputs are anticipated to significantly impact the metrology landscape related to moisture content measurement in plant-origin bulk materials. The standardised protocols and CRMs will enhance the accuracy, reliability and comparability of moisture content measurements, driving improvements in quality assessment, storage conditions, pricing and the safety of these materials. Additionally, establishing traceability to the SI units will instil confidence in the accuracy of the measurements, promoting seamless international trade and compliance with regulatory standards. This advancement will stimulate further research and innovation in the field, contributing to the continuous improvement of metrological practices and their applications in plant-origin bulk material analysis. Ultimately, this project aims to positively influence international and European food safety and trade by setting a robust foundation for standardised moisture content measurement metrology. Estimation of the water content in grain is valuable for the European Green Deal too. The EU's aim to promote resource efficiency is very close to aims of this project.

List of publications

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 June 2024, 36 months
Coordinator: Zuzana Pálková, CMI		Tel: +420606063529
Project website address: https://grainmet.cms.webnode.cz/		E-mail: zpalkova@cmi.cz
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. CMI, Czechia	8. INM, Moldova, Republic of	11. NIBULON, Ukraine
2. BEV-PTP, Austria	9. NUBIP, Ukraine	
3. CETIAT, France	10. UMTS, Ukraine	
4. DTI, Denmark		
5. INRIM, Italy		
6. TUBITAK, Türkiye		
7. UT, Estonia		
Associated Partners: 12. Mettler-Toledo, Switzerland		