European Metrology
Research Programme

EURAMET

Towards future SI measurement standards

A summary of the outputs and impact of the completed EMRP joint research projects in the SI Broader Scope theme and also projects from the Open Excellence theme.

The aim of research in these themes is to develop the International System of measurement – the SI – to meet the future measurement needs of industry and society. The research is focused on the SI units for temperature, mass, electric current and time, and on technologies required by users for its implementation.

EURAMET e.V. - the European Association of National Metrology Institutes

Measurement matters

Measurement underpins virtually every aspect of our daily lives, helping to ensure quality and safety, supporting technological innovation and keeping our economy competitive.

Supported by the European Commission, EURAMET's **European Metrology Research Programme (EMRP)** brings together National Measurement Institutes in 23 countries to pool scientific and financial resources to address key measurement challenges at a European level.

The programme is designed to ensure that measurement science meets the future needs of industry and wider society. Research is structured around six themes – Energy, Environment, Health and Industry – as well as the measurement needs of emerging technologies and the fundamentals of the SI measurement units that form the basis of Europe's measurement infrastructure.

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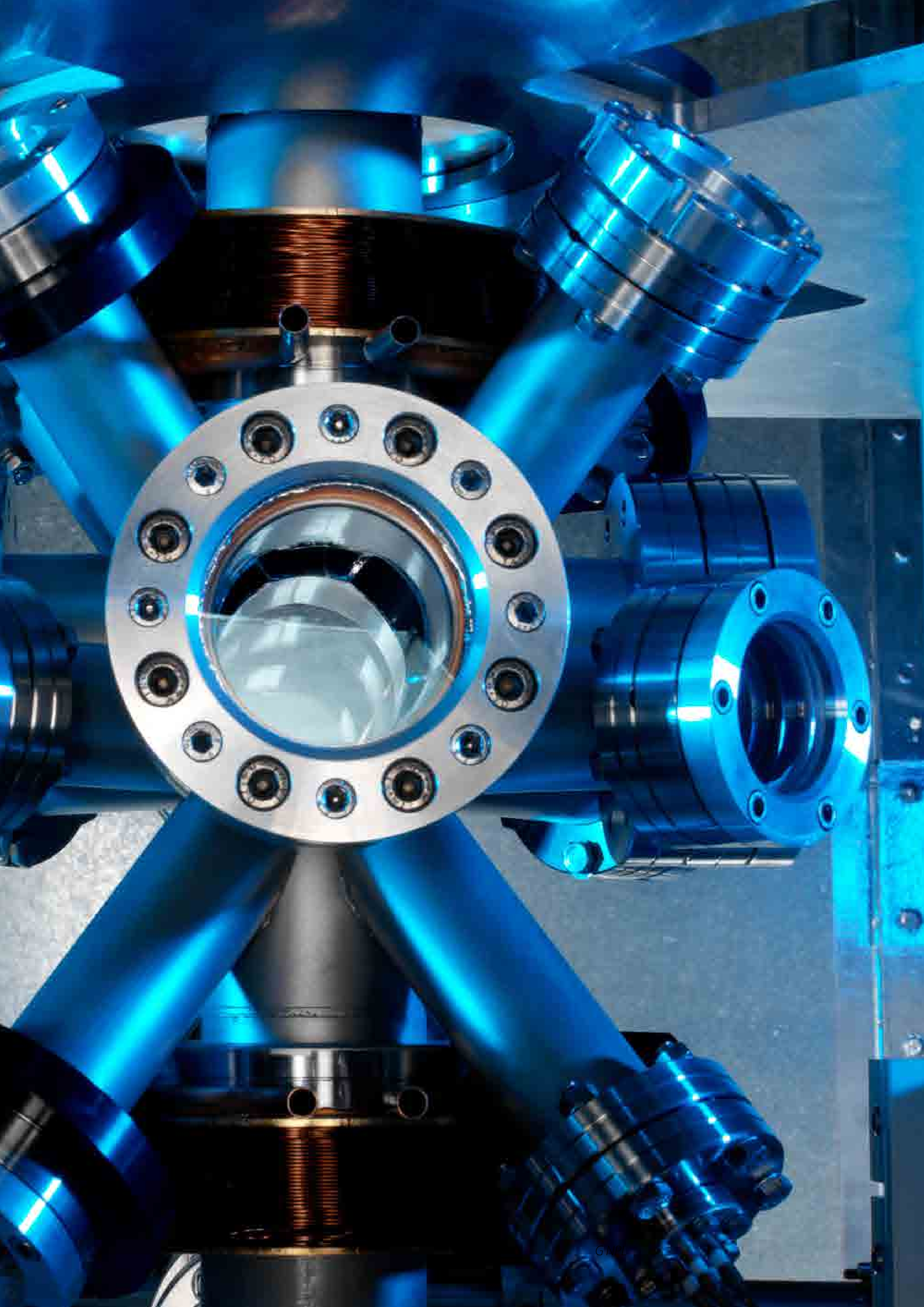
Introduction: SI Broader Scope

European manufacturers require reliable measurements that give the same answer wherever they are made. Accurate measurements, with traceability to international standards, provide an objective base for decision-making in the development and production of products and provide a basis for global trade. The solution to global challenges such as moving to renewable energy, delivering high quality healthcare and protecting the environment are all dependent on a reliable and internationally agreed measurement infrastructure. This structure supports innovation, efficient manufacturing and fair trade and underpins health, safety, security and protection of the environment.

Europe is home to some of the world's leading National Measurement Institutes (NMIs) and plays a key role in the international metrology system; defining, realising and disseminating the SI and so ensuring that measurements are the same the world over. The SI is not static but evolves to match the world's increasingly demanding requirements for measurement. The General Conference on Weights and Measures, the international body responsible for the SI, set out a roadmap outlining the route to a decision on adopting the revised SI system in 2018. This revision aims to reduce the uncertainties of measurements at the highest level, including primary measurement standards at NMIs and Designated Institutes (DIs). Ensuring that the SI continues to meet the needs of science, technology, commerce and society in the 21st century requires ongoing investment in existing and developing measurement methods and techniques. The EMRP SI Broader Scope theme addressed these challenges and supported research for the SI redefinition.

Research groups from 39 metrology institutes came together with academia and industry to conduct research under the first call of the EMRP SI Broader Scope theme. The theme focused on the metrology research needed to underpin the development of the SI system and builds on research conducted in the previous iMERA+ programme. EMRP research focused on two areas: implementation of the revised SI and development of new advanced techniques for providing traceability of measurement results for measurement users.

This report presents the key technical achievements of the research projects in the EMRP themes SI Broader Scope and Open Excellence, and their role in future-proofing the international metrology system.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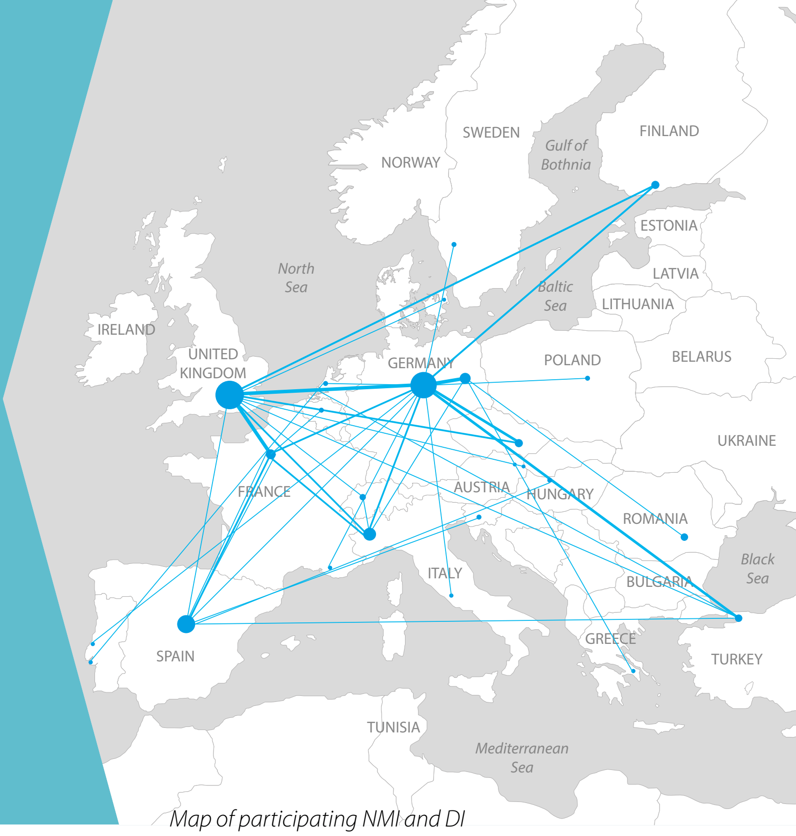
Highlights

Measurement science collaboration for the broader SI

Whether for disease diagnosis or to manufacture energy efficient engines, the SI underpins all measurements across the globe. The SI Broader Scope call has focused R&D to advance measurement standards and SI units and to prepare an efficient European measurement infrastructure based on National Measurement Institute collaboration.

The European Commission and national governments invested €143M in collaborative metrology focused research, involving research groups in 28 European NMIs and Designated Institutes (DIs), and 28 academic groups. The research addressed key needs for SI unit redefinitions and increased traceability for chemical, radio-biological and sub-nano measurements.



Map of participating NMI and DI

Direct thermodynamic measurement for kelvin

Future temperature measurements based on atomic vibrations have been brought closer as a result of EMRP funding. These atomic vibrations the basis of thermodynamic temperature, and could remove the need for complex calibration chains or even a temperature scale. EMRP funded research increased links between the existing temperature scale, the ITS-90, and this fundamental atomic property - a crucial step towards introducing this new temperature system.

Extending the current ITS-90 temperature scale's range and plugging remaining gaps are needed to increase the reliability of temperature measurements. EMRP research developed low-temperature high-accuracy thermometers enabling cryostat manufacturers and their customers to accurately demonstrate product performance with greater ease. Novel devices based on near infrared radiation thermometry or acoustic thermometry have been developed leading to commercial interest in the acoustic thermometry technology. Users will be able to make direct SI traceable thermodynamic temperature measurements for the first time.

Travelling standard for ampere generation

A future redefinition of the ampere based on single electron transport (SET) devices is now possible as a result of a highly accurate pico-amp meter developed in an EMRP project. The device is based on conventional electronics, operates at room temperature and has been validated for use with small direct currents. This innovative ultra-stable low-noise current amplifier (patent pending) provides unparalleled performance and now acts as a travelling electrical standard. Using the amplifier, the EMRP project demonstrated the superior accuracy of a SET-based cryogenic quantum ampere standard compared to state-of-the-art generation of the ampere based on 'classical' (non-quantum) experiments used in existing experimental SI ampere realisations.

Fibre optic links for future time standard

Optical clocks will provide the next generation of accurate time standards but they need to be linked to other clocks so users can benefit from time traceability directly. EMRP funding has proved that optical fibres give markedly better stability and accuracy than existing satellite-based methods and demonstrated that technologies exist to make this possible. Access to reference signals with improved accuracy impacts many applications from fundamental research and applied science, through to synchronisation of mobile telecommunication networks and navigation - all reliant on links to the SI second's physical realisation.

Silicon spheres for routine kilogram-SI links

The ability to redefine the kilo in 2018 will rely on determining the Planck constant using two different methods. One method balances a kilogram weight and a force generated by the current in a coil of wire within a magnetic field and the other relies on counting atoms in a silicon sphere. Resolving small discrepancies between the different electrical balances used to generate the kilogram experimentally and remove inconsistencies between the balancing and atom counting methods were remaining problems hampering the kilograms redefinition. The EMRP has enabled the international community to pool resources and successfully get agreement between these techniques.

Over the longer-term, the atom-counting method will make the kilogram definition accessible to any laboratory capable of carrying out surface characterisations and volume measurements. Relatively inexpensive natural silicon spheres will be usable as mass transfer standards. Spheres may transform the kilograms traceability chain and significantly increase the number of labs able to experimentally achieve an SI definition of the kilogram.

Extending chemical analysis SI traceability

SI traceability for physical measurements has existed since the 1889 introduction of the international prototype kilogram, however chemical traceability still has gaps. The lack of chemical analysis standards is limiting accuracy in industrial processes, healthcare and compliance with EU directives. EMRP funding has helped address this problem by co-ordinating the development of new methods for producing high purity single element standards. The project produced traceable high purity standards for magnesium, molybdenum, rhodium and zinc – all important for industry and healthcare. The methods used can be readily extended to other metals, increasing SI traceability and helping to resolve the gaps in chemical analysis accuracy.

First EMRP SI Broader Scope projects at a glance

Total investment €143M

Pooling expertise of 42 NMIs and DIs from 24 European countries plus the NMIs from USA, Japan, China, Australia, Canada, Russia, Mexico and Egypt

28 academic research groups

17 businesses

613 presentations at conferences

33 Articles in trade and popular press

213 presentations at workshops and seminars

146 contributions to 36 different international metrology organisations and their committees (BIPM, EURAMET, etc)

67 training courses delivered for the metrology community and 63 training courses for the scientific and end-user community

242 articles in peer-reviewed journals

Implementing the revised SI

The International System (SI) of Units is the basis for accurate measurements worldwide. The SI is not static but evolves to match the world's increasingly demanding requirements for measurement. Redefining the SI units requires improved physical experimental methods to make them available for practical purposes.

A major revision of the SI is planned for 2018, when it is expected that the kilogram, kelvin, mole and ampere will be redefined. EURAMET's European Metrology Research Programme (EMRP) supported key European research that has contributed to the SI revision by improving the determination of physical constants and developing better methods for users to access the redefined units.

Measurement challenges

The kilogram – Variations in the International Prototype Kilogram's weight – a cylinder of platinum-iridium - are affecting the precision with which accurate micro-gram drug delivery or multi-tonne grain consignment weightings can be made. Better agreement between complex measurements of the Planck constant, used in defining mass, and the way this is transferred to users via instrument calibrations are needed to support the kilogram's redefinition.

The kelvin – Industrial and research applications require temperature measurements beyond the current limits of the international temperature scale (ITS-90). New methods for accurately confirming temperatures above 1000 °C for aerospace applications or below -250 °C for determining cryostat performance are needed. In the future, fundamental atomic processes have potential uses as temperature indicators and will remove reliance on a temperature scale, but research is needed to make this a reality.

The ampere – Accurately measuring the extremely small electric currents used in miniaturised electronics relies on sensitive instruments with robust traceability to ampere standards. A new traceability chain based on single-electron transport devices and highly accurate current amplification methods is needed so industrial and research users can access the redefined ampere.

The second - Commerce, communications and navigation all rely on very precise time synchronisation. To achieve increased accuracy, the existing system based on caesium atomic clocks linked by GPS needs upgrading. Implementation of a new system based on trapped ion optical frequency standards linked using fibre-optic networks, relies on the development of new technologies and precise comparison methods.

Key technical achievements

Courtesy of PTB

The kilogram

Accurately measuring mass is fundamental to many areas of everyday life. From sophisticated manufacturing processes to microgram drug delivery or environmental monitoring – all rely on accurate weight measurements traceable to the SI kilogram. Currently the kilogram is determined by a physical artefact maintained in air at the BIPM in Paris. Copies are held around the world and periodic comparisons with the original have revealed small but significant weight changes over time. A redefinition of the kilogram in terms of a fundamental physical constant is proposed to resolve this issue.

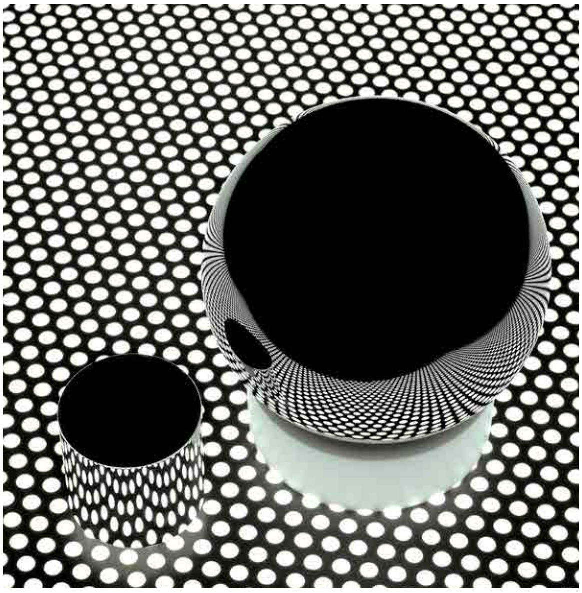
The new definition will be based on the Planck constant, and the kilogram determined experimentally either by Kibble balance experiments comparing electrical and mechanical power, or by the X-ray crystal density (Avogadro) experiment counting atoms in a silicon sphere using x-rays and optical interferometry. Both approaches are complex and costly experiments requiring a wide range of measurement skills, and specialist equipment operating under vacuum conditions.

Two iMERA+ projects, e-Mass and NAH, running from 2008 to 2011, have determined values for the Planck constant and made important contributions to the wider international redefinition activities. These projects contributed to the international decision in 2011 to base the SI redefinition of the unit of mass on the Planck constant.

International effort in this EMRP programme helped to resolve the small remaining differences between the Kibble balance and Avogadro realisations of the kilogram. This ensures confidence in the value of Planck constant so there will be no discontinuity between current and future mass measurements after the kilograms redefinition.

Kilogram redefinition - resolving discrepancies

A redefined SI kilogram will have two possible practical realisations based on the Planck constant, one based on using the Kibble balance and another based on atom counting. The EMRP project **Realisation of the awaited definition of the kilogram** refined and improved the current approaches for measuring the Planck constant to ensure experimental results from different NMI and from different experiments are consistent and available for use in the realisation of the new kilogram. It also demonstrated a successful traceability route to enable industrial users to access the redefinition of the kilogram via silicon spheres opening up the possibility of more direct SI traceability for end users.



Courtesy of PTB

The Plank constant can be experimentally determined using a Kibble balance or by the Avogadro experiment. The Kibble balance essentially operates like a traditional balance, with a mass on one side, and a current-carrying coil of wire within a magnetic field on the other. By measuring the electromagnetic force needed to balance the mass, the Planck constant can be determined in terms of quantum electrical units. An alternative approach for experimentally determining the kilogram is to relate the Avogadro constant, the number of atoms in one mole of a substance, to the Planck constant by counting atoms that form a silicon sphere.

This project sought to address the unresolved inconsistencies between these two approaches and to bring practical realisations of the kilogram by both methods into more precise agreement, through:

- **Improving the European Kibble balances** to optimise their performance for measuring the Planck constant.
- **Confirming the existing Avogadro number** by measuring the number of atoms in two pure one kilogram silicon-28 spheres constructed by the International Avogadro Coordination Project.
- **Resolving experimental inconsistencies by comparing the Kibble balance and atom counting methods** and confirming that both can generate an appropriate level of accuracy in realising the SI kilogram.
- **Participating in an international kilogram comparison exercise that demonstrated that the results of the Avogadro and Kibble balance experiments could be linked to the International Prototype Kilogram maintained by BIPM, in Paris.**

Overcoming these technical challenges has enabled the European metrology community to make an important contribution to improving the determination of the Planck and Avogadro constants. The project partners also worked with NMIs in the USA (NIST) and Canada (NRC) to eliminate the previous differences in the value of the Planck constant realised by the Kibble balance and Avogadro approaches. This brings all measurements into agreement and is an essential step in the redefinition of the kilogram.

Research conducted in this project and its precursor projects under iMERA+ have made a significant contribution to the proposed redefinition of the kilogram in 2018. The redefinition will support future improvements in the accuracy of mass and related units which supports emerging nano- and bio-technologies that require measurements on ever-finer scales.

More information is available at	SIB03 Realisation of the awaited definition of the kilogram (kNOW) http://www.euramet.org/project-SIB03
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Practical kilogram traceability for industry and research

The experimental realisation of the redefined kilogram will occur in vacuum and therefore requires the transfer of 'primary' kilogram standards from vacuum to air in order to provide traceability for end users. This creates additional sources of error, such as the sorption of surface contamination and water layers, to already complex measurement procedures.

Courtesy of PTB

The EMRP project **Developing a practical means of disseminating the redefined kilogram** developed new highly accurate mass standards, new methods to clean and monitor them, and procedures and equipment to transfer the mass standards between vacuum and air. The results of this project will help ensure the redefinition delivers benefit to the end user community.

The project:

- **Evaluated candidate metals and alloys for next-generation primary mass standards and recommended tungsten for use.** New 100 g, 500 g and 1 kg mass standards of tungsten were supplied from the project partners to the BIPM for use in their realisation experiment.
- **Developed techniques and equipment for transferring mass standards between in-vacuum and in-air conditions.** This enables the new kilogram, realised in a vacuum, to be reliably transferred to practical mass standards used in air.
- **Developed methods for storage, transport and cleaning of primary mass standards to ensure their stability over time.** This will ensure that a consistent global mass scale can be effectively maintained and disseminated after the redefinition and that the new realisation experiments can be compared and validated against each other and against the International Prototype Kilogram.
- **Conducted rigorous uncertainty analysis on the processes that will be involved in the maintenance and dissemination of the redefined kilogram** (and for smaller and large masses) to ensure robust uncertainty values can be assigned throughout the mass traceability chain.

The project has developed the procedures, equipment and skills that will ensure that mass scales based on the new SI kilogram can be reliably disseminated from NMIs to end-users via a robust calibration chain. This is essential to the implementation of the new kilogram and ensures that users with exacting accuracy requirements, from accurate micro-gram drug delivery or multi-tonne weighing of structures, can benefit from the improved mass scale.

More information is available at	SIB05 Developing a practical means of disseminating the new kilogram (NewKILO) http://www.euramet.org/project-SIB05
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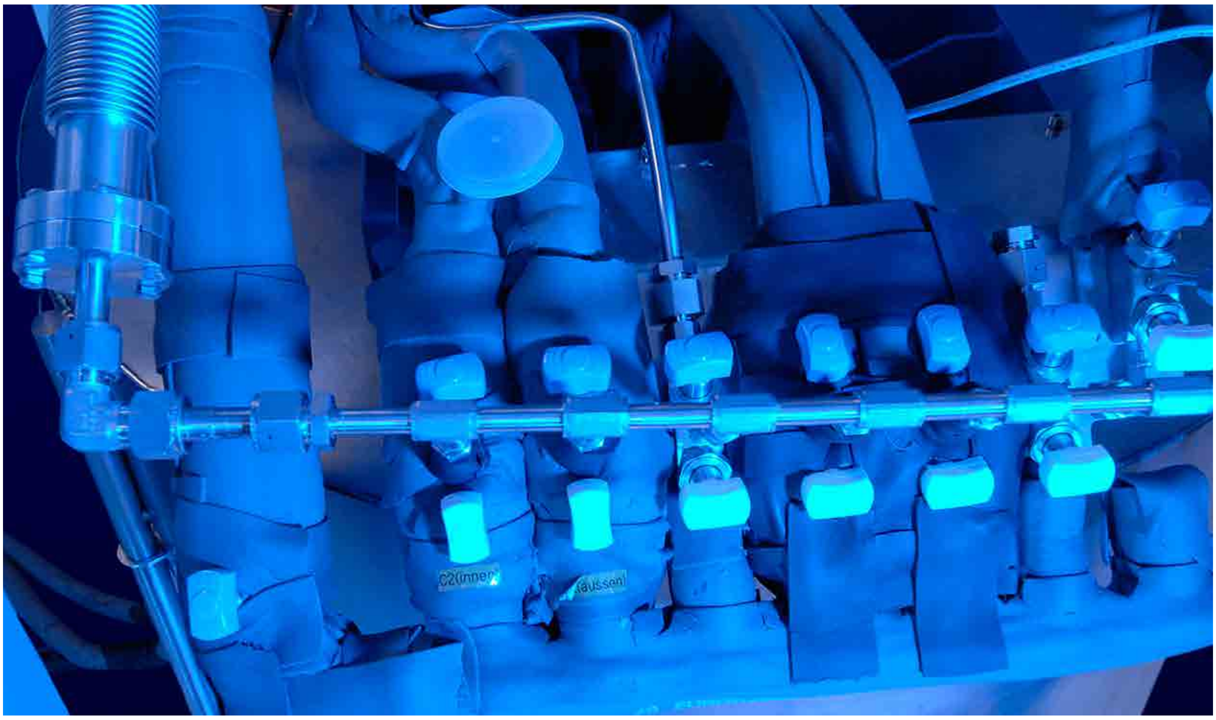


Courtesy of PTB

The kelvin

Temperature is one of the most frequently measured physical quantities in science and industry, and many industrial processes rely on high accuracy thermometry.

It is planned that in 2018 the kelvin (K), the SI unit of temperature, will be redefined. The new definition will replace one based on the triple point of water i.e. the temperature at which solid, liquid and vapour all co-exist, with one based on a fixed value of the Boltzmann constant.

Thermodynamic temperature

Think about the air in the room around you. The individual air particles are all moving at a variety of speeds, they are passing each other and colliding with each other (and you and the room walls) all of the time. The thermodynamic temperature of the air represents the average kinetic energy (the energy associated with the velocity and the mass of the individual particles) of the gas particles in the room. If sun shining through a window heats the air, then the heat energy transferred by the sunlight to the gas particles causes their average speed to increase, so the kinetic energy increases, and hence their temperature increases. Thermodynamic temperature represents the average thermal energy associated with the motion of particles and is a fundamental quantity.

ITS-90 is a practical and close approximation to thermodynamic temperature based on defined temperature fixed points such as the freezing points of silver or tin. ITS-90 is used throughout the world to ensure temperature measurement is performed reliably and uniformly which is vital for a wide variety of users in industry, medicine, weather and research.

The Boltzmann constant relates (among other things) the average kinetic energy of a gas molecule to its temperature. Its value at the time of the redefinition will be based on prior extensive international research, including previous Euramet research projects funded by the EU to enable the kelvin redefinition.

To support the introduction of the redefined kelvin and to meet on-going user traceability requirements into the 2020s, the EMRP has funded two projects. New direct thermodynamic temperature measurement methods have the potential to replace the ITS-90 and PLTS-2000 but require both development and evaluation. Improvements at high temperatures, for example, will be facilitated by new high temperature fixed points which have been developed for temperature realisation and dissemination above 1100 °C.

Implementing the new kelvin

Courtesy of NPL

Temperature measurements are difficult above 1300 K, typically present in iron, steel, and glass manufacture, and at the low temperatures used in the cryogenics industry and for quantum information processing research. Research is needed to make the redefined SI kelvin based on fundamental properties accessible to all users.

The EMRP project **Implementing the new kelvin** (InK1) addressed some of the challenges associated with practically generating and measuring thermodynamic temperature, particularly at the extremes of the international temperature scales.

The project:

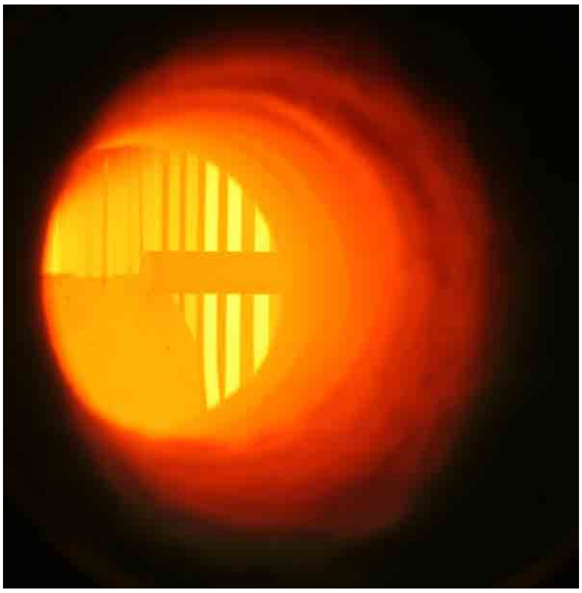
- **Constructed high temperature fixed points of precisely known melting points to enable reliable transfer of thermodynamic temperature to 2750 K.**
- **Developed methods for realising and transferring traceable thermodynamic temperatures above 1300 K directly, without using temperature scales** and is now recommending two approaches to the thermometry community for use.
- **Determined the difference between thermodynamic temperature values and ITS-90** using acoustic and dielectric constant methods and achieved the lowest levels of uncertainty to date between 25 K to ~303 K.
- **Determined the difference between thermodynamic temperature values and PLTS-2000** using three thermodynamic methods over the higher temperature part of its range (that means above 0.02 K to 1K). This in part provides the foundation for the future use of thermodynamic temperature in this range without reliance on a temperature scale.

This project has established new fixed points as reliable high temperature standards and demonstrated the feasibility of using thermodynamic temperature methods for direct temperature traceability independent of the ITS-90 temperature scale. Research will continue in the follow on EMPIR project InK2 to develop the facilities, thermometry methods and documentation that will need to be in place to support the redefinition of the kelvin. Work is ongoing for both extending the low uncertainties achieved in InK1 across the range of the ITS-90 and, in addition, down to the lowest point of PLTS-2000 (0.0009 K) and so understand and resolve the current discrepancy in data on which the PLTS-2000 is founded. These are the necessary first steps for the practical implementation of the kelvin using thermodynamic temperature with the long term aim of making direct traceability to the redefined kelvin available to a wide variety of users in industry, medicine, meteorology and scientific research without recourse to any defined scale.

More information is available at	SIB01 Implementing the new kelvin (InK1) http://www.euramet.org/project-SIB01 Details of the follow-on project InK2: http://www.euramet.org/project-15SIB02
Contact	Graham Machin (NPL) graham.machin@npl.co.uk

Novel techniques for traceable temperature dissemination

Accurate and consistent temperature measurement underpins manufacturing, health and safety as well as the development of new science and technology. Temperature measurement devices are calibrated using well-defined 'fixed points' (specific temperatures at which certain substances freeze or melt) on the International Temperature Scale of 1990 (ITS-90). However, measurements in some regions of the ITS-90 scale have larger uncertainties than others. Reducing these uncertainties will ensure that the ITS-90 can more effectively meet user needs, whilst new and emerging temperature measurement methods offer the potential for direct thermodynamic temperature measurements without using a defined temperature scale.


Courtesy of NPL

The EMRP project **Novel techniques for traceable temperature dissemination** improved the accuracy of some regions in the ITS-90 scale, and developed direct temperature measurement methods to provide a link to thermodynamic temperature, so removing reliance on the ITS-90.

The Project:

- **Improved the accuracy of a number of ITS-90 fixed temperature points** by developing methods to address key sources of measurement uncertainty, including impurities in the fixed points and temperature fluctuations in furnaces.
- **Developed four new fixed temperature point cells** to address gaps in the ITS-90 scale.
- **Improved calibration procedures for two commonly used types of standard platinum resistance thermometers**, to account for a range of environmental and internal influences that had not previously been considered or thoroughly studied (such as self-heating effects).
- **Developed temperature measurement methods independent of ITS-90 as the basis for new thermodynamic temperature standards.** These methods are based on near infra-red radiation thermometry, vapour pressure temperatures, and acoustic thermometry.

This EMRP project focused on improving the ITS-90 scale by plugging gaps through developing new fixed temperature points so reducing interpolation uncertainties and contributing to a more robust scale. In addition, the project's new CO_2 fixed temperature point may eventually provide an alternative to the mercury fixed point, overcoming issues associated with toxicity and transportation. The project's new temperature amplifier system has potential to address the lack of calibration points between 660 °C and 960 °C. Infrared radiation thermometry has undergone a significant step forward with the development of new methods and facilities for the absolute calibration of infrared thermometers and the new tuneable wavelength thermometer.

Dedicated electronics for temperature control of thermometry instrumentation and practical acoustic thermometry technology, developed by the project, are being incorporated into new commercially available devices. For the first time, users in industry and research will be able to make direct SI traceable thermodynamic temperature measurements outside NMI facilities.

More information is available at	SIB010 Novel techniques for traceable temperature dissemination (NOTED) http://www.euramet.org/project-SIB10
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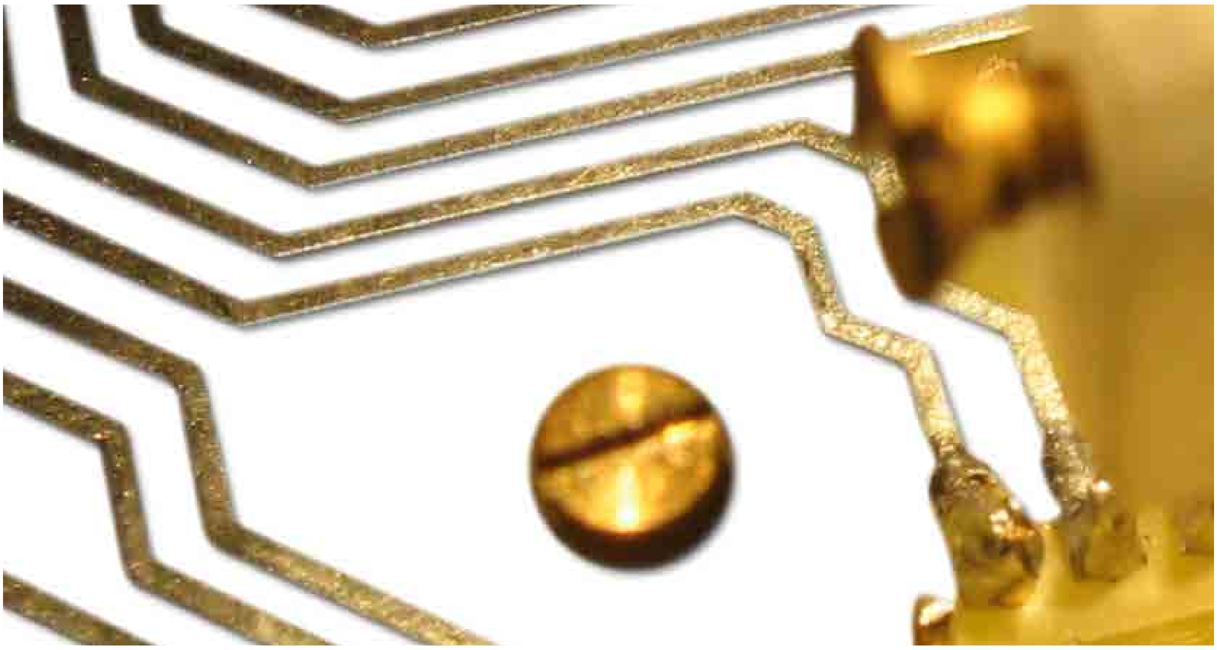


Courtesy of PTB

The ampere

It is proposed that the ampere (A), the SI unit of electric current, will be redefined (together with other base units) in terms of a fundamental physical constant in 2018. This would replace the present definition based on an ideal electrodynamic experiment, and will remove the ampere dependency on the definitions of the kilogram, the metre and the second.

The redefinition will be achieved by fixing the numerical value of a fundamental physical constant, the elementary charge e (expressed in coulomb). A practical realisation of the ampere will therefore be based on counting the number of electrons passing through a conductor's cross section in a given unit of time.

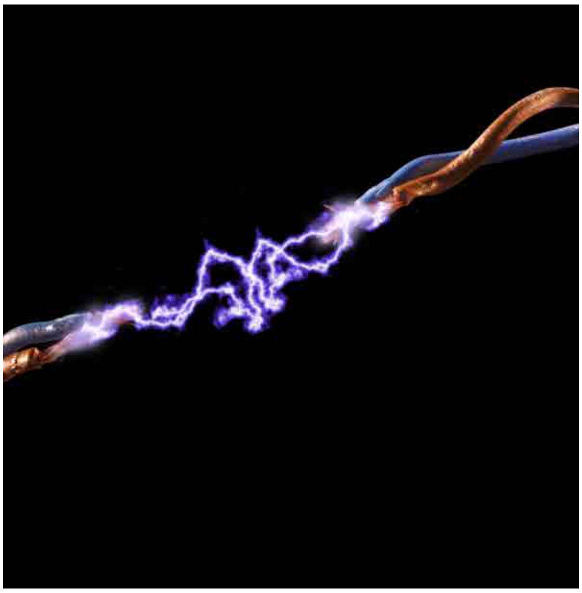
An accessible definition of the ampere that allows confident and practical realisation in measurement and calibration laboratories throughout the world is needed. A primary realisation of the unit of electric current based on counting electrons is closer to the needs of modern micro- and nanofabricated electronic devices, both in the technology involved, the working frequency, and the current magnitudes involved.

The key challenges of such a practical realisation are a) to reliably count single electrons flowing through the device at a sufficiently high rate, and b) to scale the generated current (in the 100 pA range) to larger magnitudes, of interest for calibration.

The iMERA+ project *Foundations for a redefinition of the SI base unit ampere* supported this effort and developed improved single electron pumps, single electron transport devices and error detection concepts that enables the calibration of current meters with much lower measurement uncertainties. In this programme research has continued to improve single electron pumps required for the redefinition of the ampere.

Quantum ampere: realisation of the new SI ampere

Accurately measuring small electrical currents is important in many areas of science and technology from photovoltaics, nano-scale electronics and semiconductor fabrication, to dosimetry, and environmental analysis. The redefined ampere requires a new traceability chain based on single-electron transport devices and highly accurate current amplification methods, but generating and counting electrons one by one is difficult. New and advanced concepts for single-electron error accounting using micro-chip detection require characterisation to enable labs outside the NMI community to accurately realise the ampere.



The EMRP project **Quantum ampere: realisation of the new SI ampere**, developed measurement devices and techniques to support the realisation of the proposed 2018 ampere redefinition.

The project:

- **Developed and characterised the three best existing single-electron transferal pumps** for generating currents at the 100 pA level, achieving measurement uncertainties that match the requirements of the ampere redefinition.
- **Demonstrated the first proof-of-principle of a 'self-referenced' single electron transport pump** with *in situ* detection of electron transfer errors, and established that this technique can significantly enhance the accuracy of current generating pumps.
- **Developed an innovative ultrastable low-noise current amplifier (patents pending)** with unparalleled performance and stability which can be used for the realisation of ampere traceability by calibration laboratories.

This EMRP collaboration has identified a basic characteristic of single-electron transferal devices, essential components for the realisation of the redefined ampere. The project team found that there is no 'rapid characterisation' procedure based on a series of quick measurements that can predict the accuracy of single electron transport pumps. Instead, better on-chip error accounting strategies, will have to be applied to achieve the required uncertainties of 0.1 ppm.

The ultrastable low-noise current amplifier instrument, developed in the project, is giving Europe a world leading capability in the field of ultra-accurate small current measurement instrumentation. Validated within the project as a travelling standard for small direct currents, it was commercialised by a German SME and is available for use by calibration laboratories requiring the realisation of the redefined ampere for measurements of small currents and high-value resistors.

More information is available at	SIB07 Quantum ampere: realisation of the new SI ampere (Qu-Ampere) http://www.euramet.org/project-SIB07	
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The second

The synchronisation of clocks around the world is essential for commerce, communications and navigation. It relies on precise methods for comparing frequency standards anywhere on Earth, at any time.

National Metrology Institutes (NMIs) realise the unit of time, the second, using laboratory based primary frequency standards with very low uncertainties based on the caesium-133 transition frequency that defines the SI second. Dissemination of the SI second is achieved by adjusting continuously-operating commercial clocks at NMIs to ensure direct alignment with the caesium primary standards, or via the international time scale, UTC, which is itself kept in close alignment with the caesium primary standards.

Recently, optical frequency standards based on atoms trapped at close to absolute zero temperature have achieved accuracies that exceed those of the precise NMI caesium atomic clocks. This opens up the possibility for a future redefinition of the second using optical frequency standards. In order to prepare for this, the International Committee for Weights and Measures (CIPM) are relating the frequencies of optical atomic clocks to the caesium frequency that defines the second. As the performance of optical clocks improves, these devices could provide the ideal system for international timekeeping.

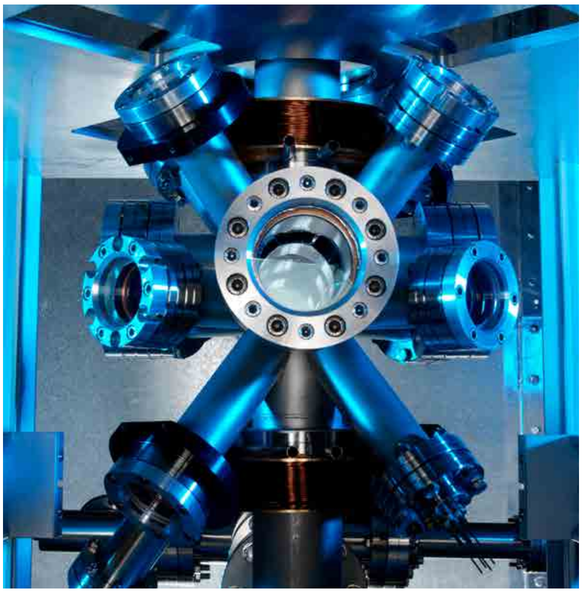
A future redefinition of the second will require an upgrade of today's atomic clocks, and currently research at NMIs is ongoing to increase the viability of optical clocks and to test the technology that will link the time signals of European national laboratories using fibre optic cables.

The SI base unit for time, the second is already defined in terms of a fundamental property of nature – the time taken for 9 192 631 770 oscillations to occur between two energy levels in a caesium-133 atom. The link between the 70 laboratories with over 420 highly accurate atomic clocks that contribute to the international time scale (Coordinated Universal Time - UTC) is made by the International Bureau of Weights and Measures (BIPM).

The Global Positioning System (GPS), designed for geographical positioning, uses accurate time and also broadcasts atomic clock time signals. But, this link between time signals around the world does not provide the stability required for highly precise comparisons of the best available optical clocks in different countries. Introducing an optical fibre network across Europe would give greater accuracy and an order-of-magnitude better stability compared with satellite-based methods, so upgrading future linking of optical time and frequency standards.

High-accuracy optical clocks with trapped ions

Atomic clocks form the basis of international time keeping and are widely used in navigation, communications and computer network management. A new generation of atomic clocks that is based on optical reference frequencies rather than on microwaves promises significantly improved accuracy and stability. Ultra-precise optical clocks using laser-cooled trapped ions could provide the new frequency standards needed for a future redefinition of the second but their operational performance needs to be optimised so that this can happen.



Courtesy of NPL

The EMRP project **High-accuracy optical clocks with trapped ions**, developed a selection of trapped ion optical clocks as potential successors for the current primary NMI-based caesium atomic clocks. The project optimised their design and generated data to assess their performance.

The project:

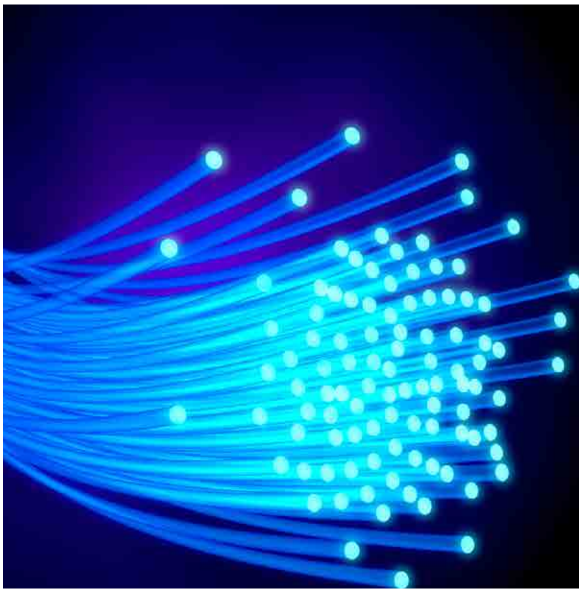
- **Developed more advanced ion trap designs for single and multiple ions** which minimise heat load and temperature differences in the trap structure under real operating conditions. These are major contributors to measurement uncertainties for these types of frequency standards.
- **Developed novel and efficient methods to generate the laser radiation required to excite and cool the trapped ions**, an important milestone in the realisation of a new optical frequency standard.
- **Performed measurements of absolute frequencies generated by single-ion optical clocks** against primary caesium clocks to ensure optical frequency standard traceability.
- **Performed the first comparison of remote single-ion optical clocks using the Global Positioning System** and geodetic data processing. This demonstrated that this world-wide method for frequency transfer can be used in assessing the precision of optical clocks.

This EMRP project has taken a significant step towards a future redefinition of the second based on optical frequency standards. Efficient sharing of next generation ion traps developed in the project, has resulted in two new highly accurate European optical clocks. Optical clocks based on trapped ytterbium ions have been demonstrated to have the highest accuracy of all the various types of trapped ion optical clocks presented so far, making them suitable candidates for next generation frequency standards. These particular ion based optical clocks offer a very favourable combination of operational reliability and high accuracy for future realisations of the second.

As a result of the project's experimental comparison of optical and atomic caesium based clocks, international agreement has been reached on ytterbium reference frequencies that can now be used as representations of the SI seconds in the optical frequency range.

More information is available at	SIB04 High-accuracy optical clocks with trapped ions (Ion Clock) http://www.euramet.org/project-SIB04
Contact	Ekkehard Peik (PTB) ekkehard.peik@ptb.de

Network for European time and frequency transfer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Today's best clocks rely on transitions in the optical frequency domain. They outperform the best caesium-based atomic clocks in both accuracy and stability. However, a future SI realisation of the second, based on optical atomic clocks, will need a system capable of transferring time and frequency traceability with greater accuracy than the well-established, satellite-based time and frequency systems can achieve.

The EMRP project **Network for European time and frequency transfer** investigated the techniques needed to ensure accurate optical time and frequency transmissions across Europe using optical fibres. A major achievement of this project was the demonstration that fibre optic frequency transfer will offer orders-of-magnitude better stability and accuracy than existing satellite-based atomic clock comparison methods.

The project:

- **Developed a versatile tool box for establishing optical, long-distance time and frequency links including performance assessment and fault detection.** This opens the way to accurate and high-resolution optical clock frequency comparisons over international fibre networks.
- **Developed and performance tested a 2000 km dedicated fibre-optic link** suitable for comparing frequencies generated by optical clocks.
- **Developed optical regeneration methods and demonstrated a 1500 km stable fibre-optic link** using a shared public telecommunication network, showing that dedicated links may not be required between the frequency generator and its user.
- **Established and characterised bi-directional fibre-optic links between NMIs** enabling the first international comparison of optical clocks without the use of satellite-based systems.
- **Developed protocols and techniques for accurate time transfer accessed** at the levels of precision required for the international atomic time scale.

This EMRP project has successfully transmitted optical frequency and timing signals over longer distances with greater accuracy and stability than previously possible, using both dedicated and commercially available optical fibres. With access to such fibres, it is now possible for users in research and commerce to benefit from highly accurate time and frequency standards that were previously only available at NMI's. The linking of NMI based atomic clocks by fibre-optics will eventually offer a viable and more accurate back-up system for Co-ordinated Universal Time - the international standardised time signal for telecommunications, finance and the internet.

As a result of the project a first step towards a European scientific network has been realised that enables optical atomic clock comparisons at the highest level of accuracy. This is a significant step towards the proposed SI redefinition of the second using more accurate optical atomic clocks to replace current caesium atomic clocks.

More information is available at	SIB02 Accurate time/frequency comparison and dissemination through optical telecommunication networks (NEAT-FT) http://www.euramet.org/project-SIB02
Contact	Harald Schnatz (PTB) harald.schnatz@PTB.de

Metrology for the SI Broader scope

The strategic aim of *SI Broader Scope* was to underpin the development of the SI system through R&D in fundamental and applied measurement science. It specifically addressed two areas, the first was in support of the SI unit redefinitions and the second was in the development of advanced techniques for measurement traceability to support emerging requirements in a variety of fields. Projects in this second area worked to improve the underlying needs for sub-nano length measurements, radiotherapy cell biology and chemical analysis using high purity elemental standards.

Measurement challenges

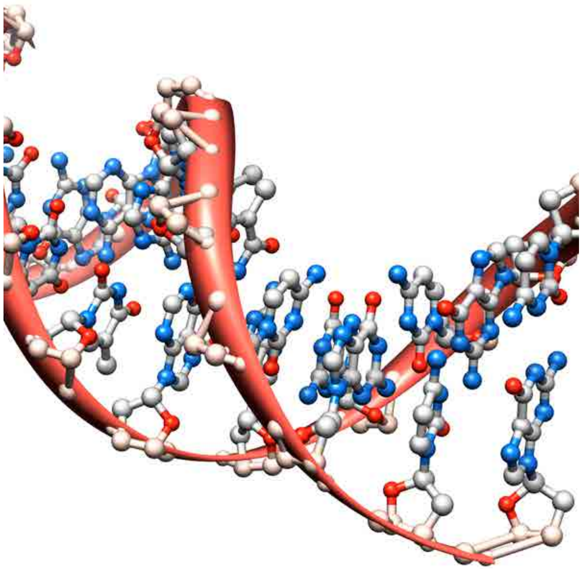
Traceability of sub-nm length measurements - The interferometric measurement of large scale dimensions with sub-nanometre accuracy is needed for both cutting-edge projects like the redefinition of the kilogram, and also for high precision products, such as next generation computer processors which rely heavily on accurate mask positioning during the numerous steps in the lithography process.

Biologically weighted quantities in radiotherapy - X-ray and gamma radiotherapy doses are based on the absorbed energy from the radiation beam delivered to water – the main constituent of the human body. However with the development of cancer therapies using proton or ion beams an additional weighting factor is required to relate the increased cell damage caused by these therapies to the more conventional high-energy x-ray or gamma therapy beams.

Primary standards for challenging elements - Chemical analyses play a key role in many aspects of everyday life including regulating environment quality, ensuring health and assisting industrial productivity. Standards in chemistry are usually materials of known purity providing a vital link to the SI, but due to the difficulty and complexity of accurate elemental characterisation, few validated standards are available for use.

Key technical achievements

Biologically weighted quantities in radiotherapy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High energy proton and carbon ion beam therapies form the basis of emerging treatments for radiation resistant cancers. These treatments offer more accurate targeting of tumours with less damage to surrounding healthy tissue compared to conventional therapies. Biological weighting factors are used to relate delivered treatment energy to the damage it causes at the cellular or DNA level. However significant variations exist in weighting factors derived from different types of therapy beam and from different research centres. This makes reliably comparing patient outcomes for similar treatments difficult.

The EMRP project **Biologically weighted quantities in radiotherapy** brought together clinicians, biologists and physicists in a collaboration to improve the determination of dose weighting factors and used a multiscale approach to combine dose effects to the cell (microdosimetry) and to its DNA (nanodosimetry).

The project:

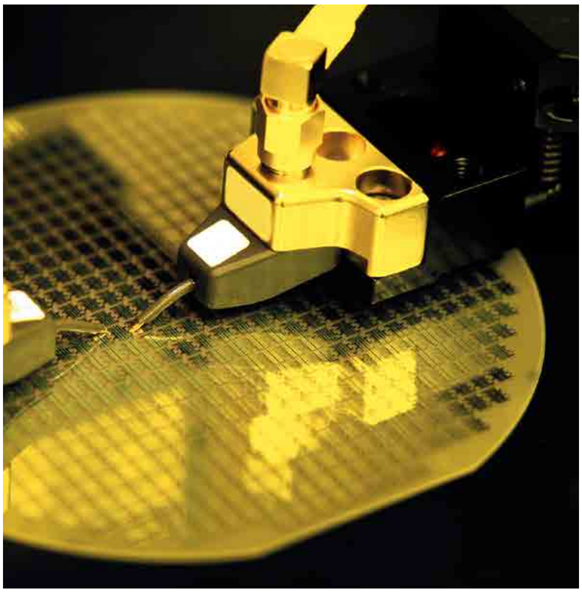
- **Demonstrated that micro dosimeters can be used in a clinical environment** to characterise ion beams and their biological effects.
- **Demonstrated that nanodosimeters can be used for consistent characterisations of microscopic energy deposition** patterns made by therapeutic ion beams. This is important for determining the correct dose delivery using different types of radiation.
- **Developed better simulations of radiation damage based on DNA properties.** These remove reliance on the approximation that the human body consists entirely of water.
- **Linked physical doses and the predicted treatment outcomes** to enable radiotherapy centres to compare and combine results.

The project examined how radiation therapy beams cause damage to living cells and DNA molecules, and designed multi-scale mathematical models and computational tools for predicting radiation damage to cells. Coupled with the project's new radiation quality weighting factors which relate dose to the damage it causes in targeted tissues or cell DNA, the project results will help pave the way for optimised and better targeted patient treatment protocols.

The concepts linking radiation damage to exposure developed in this project will also have uses in a wide range of other areas, such as environmental exposures to low-doses of radon gas, occupational exposures of radiation workers and accidental radiation exposures.

More information is available at	SIB06: Biologically weighted quantities in radiotherapy (BioQuaRT) http://www.euramet.org/project-SIB06	
Contact	Hans Rabus (PTB)	hans.rabus@ptb.de

Traceability of sub-nm length measurements



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Confirming the performance of precise milling machines, manufacturing disk-drives and assembling semiconductors all rely on accurate sub-nanometre dimenson measurements. The highest accuracy measurements of length, or thickness, are made with non-contact techniques and use optical interferometers to determine length or displacement precisely. Capacitive displacement sensors enable measurements in more challenging environments, where air, vibrations and noise make the use of interferometers impractical, or too expensive. Accurate measurements on the sub-nanometre scale require consistent modelling of the measurement system as well as accurate comparisons of differing measurement techniques and a reduction in measurement uncertainties.

The EMRP project **Traceability of sub-nm length measurements** enabled improved traceability to the SI for sub-nanometre range length measurements made by optical interferometers and improved calibration methods for capacitive sensors used for measuring nano-sized component movements.

The project:

- **Established a method to model, evaluate and correct systematic errors in interferometer setups.** Adequately correcting for systematic errors will make a significant contribution to lowering the measurement uncertainties of current high-end optical interferometers.
- **Developed a new calibration procedure for capacitive sensors** with corrections for temperature, pressure, humidity, tilt and edge effects. These methods will enable the accurate and traceable calibration of high-end capacitive probe systems.
- **Developed improved NMI capabilities for measuring length with reduced uncertainties** which were confirmed by a comparison exercise.

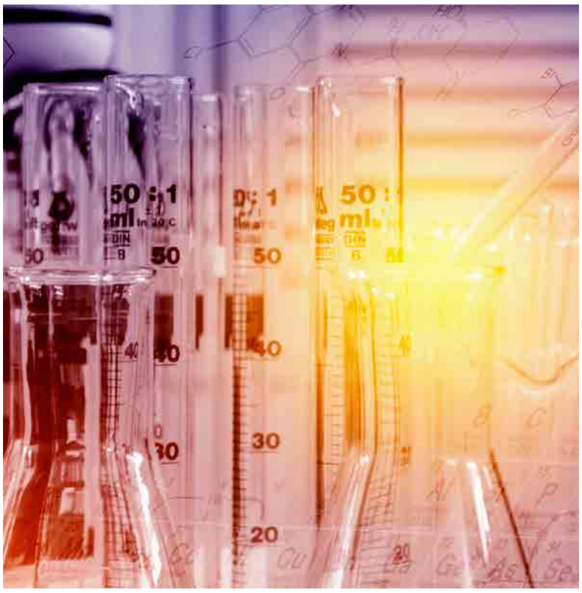
This multidisciplinary EMRP project used capacitive sensors, unique x-ray interferometers and the highest accuracy optical interferometers to develop a leading capability for sub-nanometre length measurement in Europe. This project brought together industrial and scientific measurement experts to deliver best practice and precise nano-measurement methods to a multitude of industrial applications reliant on nanometre precision dimension measurements.

Industrial demand was not the only motivation for increasing the accuracy of subnano dimension measurements. The SI redefinition of the kilogram based on atom counting of silicon spheres is dependent on precisely determining the separations of the sphere's atoms. This could only be achieved using the tools developed in this project for measuring sub-nano distances with great accuracy.

More information is available at	SIB08: Traceability of sub-nm length measurements (subnano) JRP website address: http://www.euramet.org/project-SIB08	
Contact	Birk Andreas (PTB)	birk.andreas@PTB.de

Primary standards for challenging elements

Millions of chemical analyses for different elements are performed every year in Europe. They enable accurate measurements for directives such as the In vitro diagnostic devices directive for laboratory medicine (IVD) or the EU Water Framework Directive (WFD) for environmental protection, as well as general requirements of international standards (e.g. ISO/IEC 17025). However, only a few pure single element solution standards with fully demonstrated SI traceability exist. Extending this number, and especially determining the standardisation methods for challenging elements, will increase comparability of chemical measurement results in both traditional and emerging product applications.



The project **Primary standards for challenging elements** developed procedures and methods for realising SI traceable solution standards for four industrially important elements with potential for extending standard solution production to other chemically similar elements.

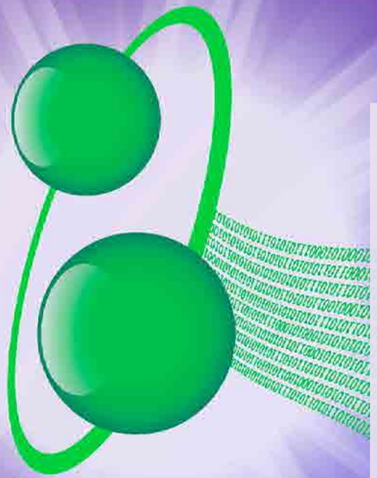
The project:

- **Developed methods for preparing high purity samples of magnesium, zinc and aluminium in both solid and liquid forms** with well characterised impurities and low uncertainties.
- **Developed new reference materials for magnesium and for molybdenum containing well characterised ratios of different isotopes** and used these for the calibration of mass spectroscopy instruments for chemical analyses.
- **Demonstrated for the first time the comparability of results from advanced mass spectroscopy and more traditional isotope fractionation** - techniques important for determining the quantity of specific isotopes present in samples containing mixes of isotopes of a single element.
- **Developed methods for complete and loss-free digestion of virtually inert refractory elements molybdenum and rhodium** enabling the preparation of primary elemental solutions.

This EMRP project increased the number of existing well characterised and SI traceable high-purity elemental solution standards. As a collaboration between eight European National Measurement Institutes and Designated Institutes, the project was able to pool expertise and resources to achieve more than any individual organisation on its own.

Although this project addressed SI traceability for only four key industrial elements, the solution preparation methods and improved rigour in isotopic sample evaluation will apply to many related elements in the periodic table. The new high purity solution standards for key industrial metals are now giving SI traceability across many of the millions of chemical analyses performed each year and contributing to the founding of a robust chemical measurement system that is fundamental for innovation in science and technology.

More information is available at	SIB09 Primary standards for challenging elements (ELEMENTS) Project website address: http://www.euramet.org/project-SIB09	
Contact	Heinrich Kepphardt (BAM)	heinrich.kipphardt@bam.de

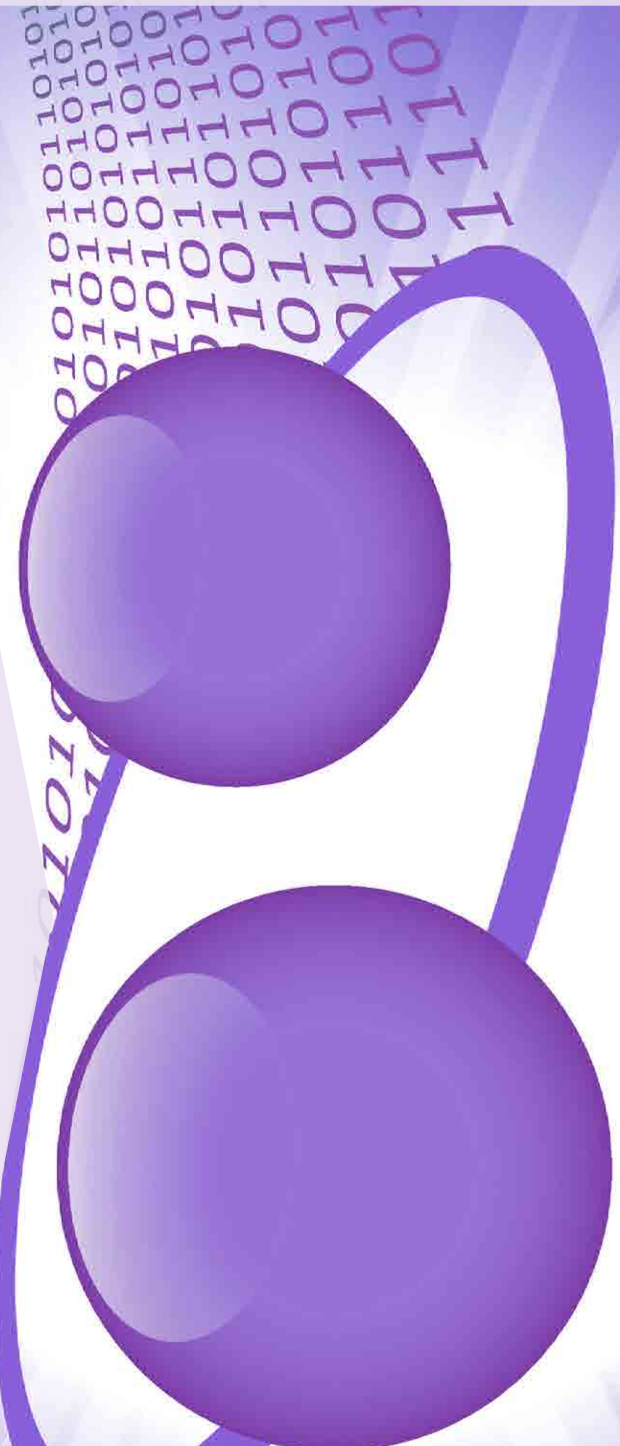


Introduction: Open Excellence

The EMRP Open Excellence theme was set up to fund early stage scientific research for future measurement techniques. To encourage interaction between the NMI community and academia, funding was made available to support the participation of university researchers.

Smaller in scale than other EMRP themes, Open Excellence was targeted at scientific fields that had not been included in other EMRP calls and projects were selected for scientific 'excellence'.

A forerunner to the EMPIR Fundamental Theme, projects on aspects of quantum mechanics were funded.



Measurement challenges:

Quantum technologies are set to revolutionise computing applications in the 21st century and require fundamental research to facilitate progress towards adoption. The four selected projects in this theme all performed fundamental research into future measurement methods as a first step towards characterising quantum properties of materials or devices that will be used in next generation applications.

Aspects of quantum mechanics investigated in the Open Excellence theme:

- Quantum tools for better timekeeping and sensing
- Tools for calibrating optical quantum devices
- Tools for microwave single photon measurements
- Tools for measuring properties of quantum electron spin.

Key technical achievements

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Quantum tools for better timekeeping and sensing

Quantum mechanics has the potential to generate, detect and use the states of atoms or ions for precise optical clocks and frequency standards. Uses for such optical clocks include: next generation global navigation systems, exploring fundamental physical laws for experimentally generating the second. Currently the time it takes for an optical clock to stabilise and produce a steady response is prohibitively long and prevents easy comparison of individual optical clock frequencies. A possible solution is to use Frequency standards based on quantum entanglement. This is a phenomena where two atoms exhibit the same properties as one another without being physically linked.

The project **Quantum engineered states for optical clocks and atomic sensors** demonstrated improved optical clock stability and frequency accuracy in a variety of systems using new quantum engineering methods.

The project:

- **Developed, tested and characterised ion traps on 4 inch wafers** able to produce multiple ions with quantum entangled states and assessed the ions suitability for next generation optical clocks.
- **Developed key technologies for future ultra-stable oscillators** based on quantum engineered atomic states.
- **Demonstrated optical clock stability with close to 10^{-16} uncertainty** at one second using state-of-the-art ultra-stable lasers.
- **Investigated the use of entanglement as an optical frequency standards** both theoretically and experimentally for precision spectroscopy applications.

As well as optical clocks this project will impact on atom interferometry, quantum gases, and quantum information processing. Limitations faced by optical clocks are similar to the limitations in other atom-based sensors, such as accelerometers, gravimeters, gyrometers or magnetometers.

More information is available at	EXL01: Quantum engineered states for optical clocks and atomic sensors (QESOCAS) http://www.euramet.org/project-EXL01
Contact	Sébastien Bize (LNE-SYRTE) sebastien.bize@obspm.fr

Tools for calibrating optical quantum devices

Next generation ultra-secure communications, super-fast computing and enhanced optical measurement techniques are all potential uses for photons of light – a form of quantum energy. Using existing lasers to create single photons, it is not possible to meet the demanding requirements of emerging quantum mechanics technology. New compact and easier to use single photon sources that can be incorporated into quantum optics and measurement applications are needed.

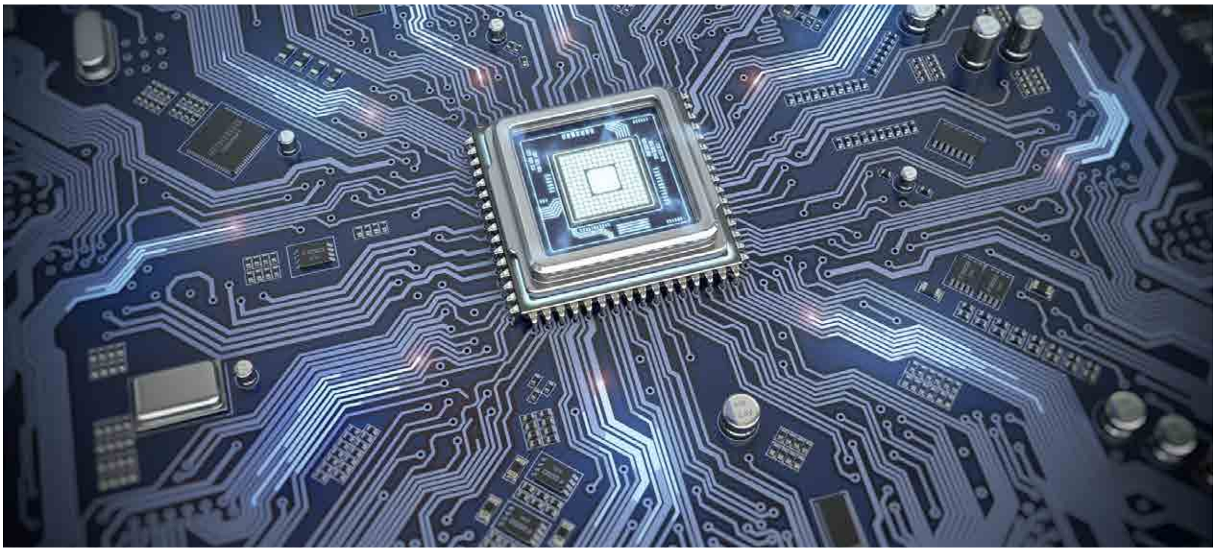
The project **Single-photon sources for quantum technologies** developed single photon sources and measurement techniques enabling, for the first time, the reliable characterisation of quantum sources by European NMIs.

The project:

- **Developed pulse driving electronics for single photon sources** capable of operating at less than a nano-second and with adjustable frequency for generating increased numbers of photons so supporting development of better and easier-to-use single-photon sources.
- **Developed simplified analytical models of quantum-dot single photon sources** and used them to identify and overcome engineering challenges during single photon source development.
- **Developed a single-photon source** which has potential for use in detector calibration.
- **Developed a switched integrator amplifier for characterising single-photon sources** enabling the direct measurement of single-photon fluxes with standard (analogue) silicon based photodiodes.

This project addressed limitations to the broad application of single-photon sources, i.e. their low reliability, low efficiency and impracticability in use. Through collaboration, the individual expertise from each NMI and university was utilised to develop single-photon sources for real world applications, not only for quantum information and communication, but also for entanglement enhanced measurements. As a result, the project's new technologies will assist researchers and industrialists to develop new applications and measurement techniques.

More information is available at	EXL02: Single-photon sources for quantum technologies (SIQUTE) http://www.euramet.org/project-EXL02
Contact	Stefan Kück (PTB) stefan.kueck@ptb.de



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Tools for microwave single photon measurements

Real-time single microwave photon detection is an emerging capability in quantum mechanics applications, such as quantum computing, quantum measurements and in ultrasensitive spectroscopy in cryogenic environments. However, unlike optical quantum detection, there are no detectors that can reliably resolve single microwave photons. A fundamental reason for this is the much lower energy of the microwave photon compared to that of an optical photon. This means that detecting microwave photons relies on extremely sensitive detectors, operating in highly shielded environments at ultra-low temperatures. New single microwave photon technologies are required to improve the performance and sensitivity of quantum microwave devices and so reduce background effects in cryogenic environments to promote the development of on-chip microwave components.

The EMRP project **Controlling single-photon microwave radiation on a chip** developed single photon microwave sources and detectors and investigated the sources of interference in cryogenic measurement systems.

The project:

- **Developed single-microwave-photon detectors** for use between 8 GHz and 80 GHz based on superconductor and semiconductor nanotechnologies.
- **Developed and characterised two types of single microwave photon sources** which are suitable for integration with superconducting-normal metal-superconducting thermal detectors.
- **Determined for the first time, the frequency and power function responses of a cryo-electronic quantum nano-detector** using on-chip-generated microwaves.
- **Constructed a measurement chamber for studying the effects of microwave background radiation on cryo-electronic devices.**
- **Used external magnetic fields to prevent background microwave photon interference effectively** via on-chip leads during microwave measurements.

In this project, for the first time experiments using on-chip microwave technologies for generating, transmitting and detecting microwaves were performed. These advances support the development of signal amplifiers for wireless communications and radiation measurements. The project's microwave photon detectors and sources have the potential to assist in the characterisation of novel microwave applications including the realisation of practical quantum computing based on solid-state qubits.

More information is available at	EXL03: Measurement and control of single-photon microwave radiation on a chip (MICROPHOTON) http://www.euramet.org/project-EXL03
Contact	Antti Manninen (VTT) antti.manninen@vtt.fi

Tools for measuring properties of quantum electron spin

Nano-scale magnetic technologies could be used in applications as diverse as high-density low-power data storage and more sensitive diagnostic tools for bio-sensing. Understanding the motion of magnetic regions in nanowires and how interactions of electron spins and thermal gradients effect the wires magnetic properties are key. Researchers need robust measurement methods for reliably characterising fundamental quantum material properties as a precursor to introducing electron spin technologies into new applications.

The EMRPs project **Spintronics and spin-caloritronics in magnetic nanosystems** developed and characterised several magnetic nanodevices. These were then used to generate an understanding of the interplay of spin-polarised transport and thermal gradients within the devices.

The project:

- **Optimised fabrication processes for magnetic boundaries in nano-devices** and performed detailed spin characterisations over a broad temperature range.
- **Characterised the efficiency of thermo electrical power generation in spintronic devices** for the first time and found that the thermo electrical efficiency can be changed by more than 60% when magnetisation is reversed.

The fundamental research performed in this project has introduced measurement reliability for the interaction of electron spins and heat currents and has enabled the first international comparison of these types of measurements. Coupled with the discovery of thermo-electric power changes with reversal of magnetic field direction, there is now the potential for using this phenomena in susceptible materials for the external operation of electronic devices without the need for connections.

The methods developed in the project provide best practice for generating reliable measurements for spintronics and thermal effects. The IEC Technical Committee, *Nanotechnologies for standardisation of nano-scale magnetic field measurements,* has started drafting a new measurement standard in this emerging technological field. The EURAMET EMPIR project *Nano-scale traceable magnetic field measurements* is continuing to support measurement research in this field.

More information is available at	EXL04: Spintronics and spin-caloritronics in magnetic nanosystems (SpinCal) http://www.euramet.org/project-EXL04
Contact	Hans Werner Schumacher (PTB) hans.w.schumacher@ptb.de

Further information

More detailed information on the EMRP SI Broader Scope and Open Excellence projects' outputs and the contact details for each project can be found at:

https://www.euramet.org/emrp-health-si-newtech-2011
https://www.euramet.org/emrp-industry-si-excellence-2012

Other EMRP and EMPIR projects can be found at:

https://www.euramet.org/research-innovation/emrp/emrp-calls-and-projects/
https://www.euramet.org/research-innovation/research-empir/empir-calls-and-projects/

Europe's National Measurement Institutes working together

The majority of European countries have a National Metrology Institute (NMI) that ensures national measurement standards are consistent and comparable to international standards. They also investigate new and improved ways to measure, in response to the changing demands.

While traditional metrology stakeholders in manufacturing demand ever-increasing scope and greater accuracy, there is also a greater demand for accurate measurement in areas which support food safety, clinical medicine and environmental quality, as well as emerging areas such as biotechnology and nanotechnology. This requires resources beyond the scope of most national metrology systems and therefore it makes sense for NMIs to significantly increase the level of collaboration with each other. **The European Association of National Metrology Institutes (EURAMET)** is the body that coordinates collaborative activities in Europe.

EURAMET has implemented the European Metrology Research Programme (EMRP), a project programme organised by 23 NMIs and supported by the European Union, with a value of over €400M. The EMRP facilitates the formation of joint research projects between different NMIs and other organisations, including businesses, industry and universities.

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