



## Future proofing the SI

A summary of the outputs and impact of the completed EMRP joint research projects in the SI Broader Scope II theme.

The aim of this theme's research was to further develop the International System of measurement – the SI – to meet the future measurement needs of industry and society. Research focused on future proofing the SI units that are important in electronics and communications and also on promoting improved links to SI units for measurement traceability, standardisation, and regulatory compliance in a selection of key applications.

# Measurement matters

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

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

The programme was designed to ensure that measurement science meets the future needs of industry and wider society. Research was structured around the 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.

# Contents

- Introduction: SI Broader Scope II ..... 4
- Highlights..... 6
- EMRP SI Broader Scope II projects at a glance ..... 8
- Future proofing the SI units for communications and electronics ..... 10
  - Measurement challenges ..... 10
  - Key technical achievements ..... 11
- Improved links to the SI units for specific applications ..... 16
  - Measurement challenges ..... 16
  - Key technical achievements ..... 17
- Improving standardisation and the demonstration of regulatory compliance ..... 21
  - Measurement challenges ..... 21
  - Key technical achievements ..... 22
- Focus on Impact ..... 27
- Further information..... 34

# Introduction: SI Broader Scope II

**A reliable and internationally agreed measurement infrastructure is essential for addressing global challenges, ensuring regulatory compliance and supplying industries with compatible components that are fit for purpose. This infrastructure also supports innovation, and underpins health, safety, security and environmental protection strategies.**

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 International System of Units – the SI – which ensures measurements are the same the world over. The SI is not static but must evolve to match the world's increasingly demanding requirements for measurement. Research is needed to enable SI unit practical realisations to increase in accuracy and to ensure robust links between these realisations and user communities in science, technology, commerce and society. This requires ongoing investment in existing and new measurement methods and techniques.

EURAMET's EMRP SI Broader Scope II theme addressed these challenges and supported research for:

- Future proofing the SI units important in electronics and communications
- Promoting greater measurement standardisation and regulatory compliance
- Improving links to the SI units for specific measurement applications.

Research groups from 34 metrology institutes came together with academia and industry to conduct research in the second EMRP SI Broader Scope theme. This report presents the key technical achievements of the 14 research projects in this theme, and their role in future-proofing the international metrology system.



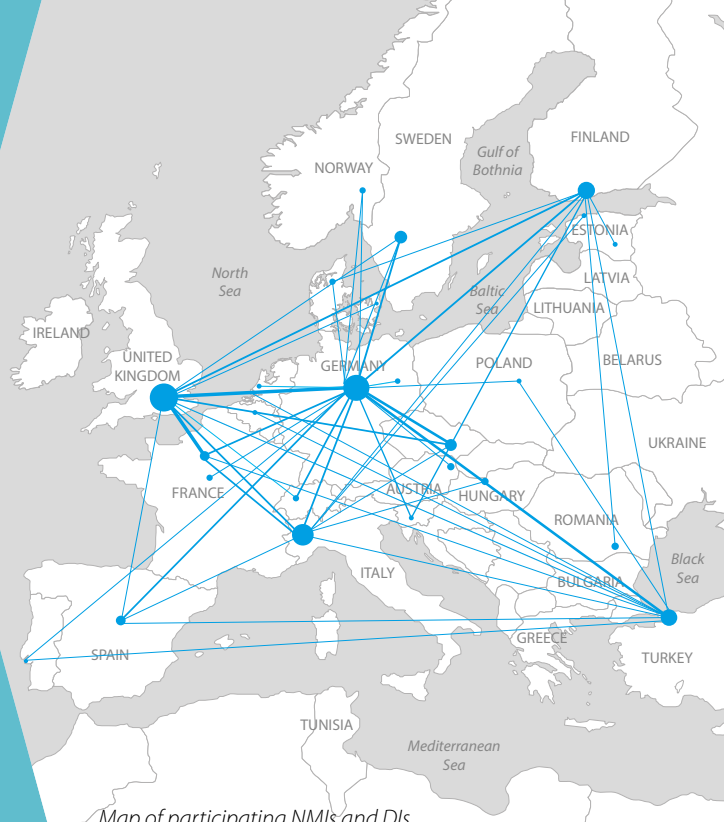


# Highlights

## Measurement science collaboration for the broader SI

This EURAMET EMRP theme has enabled the European metrology community to work collectively towards new methods for practically realising SI units, improving links to the SI units for specific applications that are important in industry and also for underpinning regulatory compliance. The projects have brought together metrology expertise in physics, chemistry, and biology to develop new analytical methods and approaches which support increased accuracy across a wide range of areas from nanotechnologies to healthcare and environmental regulatory compliance.

The European Commission together with national governments have invested 50 million euro in collaborative research projects, involving research groups in 20 European NMIs and Designated Institutes (DIs), 21 academic groups, and 5 businesses.



Map of participating NMIs and DIs

## Demonstrating graphene's potential as a future SI resistance standard

Advances in sensing application and communication electronics have outstripped existing measurement capabilities. For measurement science to keep up with innovations it must develop new techniques for experimentally realising the SI electrical units of resistance, impedance and voltage.

Linking resistors, used in sophisticated circuits, to the Ohm - the SI unit of resistance - relies on measurement instruments with traceability to highly accurate NMI Quantum Hall Effect (QHE) resistance standards. Two-dimensional graphene, with its remarkable electrical properties has great potential for use in future NMI resistance standards, but making it reliably is difficult.

EMRP researchers have successfully manufactured resistance grade graphene, characterised it and then demonstrated that it produces the QHE at higher temperatures and lower magnetic fields than existing resistance standards. This confirms the feasibility of using graphene in future SI realisations of the Ohm and that it has the potential to make simpler experimental set-ups available to more calibration facilities. Further development is needed before these novel standards can be considered for use as SI units.



## Innovation in optical measurement standards

Optical technologies are important for many applications from fibre optic communication networks to earth observation and healthcare. To take advantage of LED technologies, new highly accurate measurement standards are needed to support SI traceability in radiometry – the measurement of light in any part of the electromagnetic spectrum. EMRP research has developed a new radiometry standard based on Predictable Quantum Efficiency Detectors (PQED) that for the first time can be easily used by calibration and testing laboratories, improving access to the candela, the SI unit of luminous intensity. The PQED provides a direct link to the fundamental constants used in the SI redefinition, therefore it does not require calibration using any other method.

## A milestone in angle metrology

Ensuring that the world's most precise mirror, to be installed in the new European X-ray Free Electron Laser Facility (XFEL) in Hamburg (Germany) is defect free, relies on measurement technology that can identify system imperfections of only a few atoms in size. EMRP research has enabled manufacturers of optical components for the beam line to demonstrate conformance to onerous specifications. Working at the boundaries of measurement capability, the project developed advanced facilities and a new two-axis calibration method for the autocollimators that are used to make contactless angle measurements of complex optical surfaces. Improving the quality of high intensity light beams supports European materials research which is fundamental to future innovations in many scientific fields, such as improved films for solar panels.

## Developing next-generation SI impedance standards

Precise measurements of impedance – the resistance a circuit presents to an alternating current – is vital in modern electronics. Impedance values are currently defined using the Quantum Hall Effect, which can be scaled to create a range of impedance values depending on the number of windings in the transformers used. Josephson Bridges, based on dual alternating current Josephson voltage standards, enable unprecedented flexibility in high-precision impedance calibrations but these take a long time to achieve stability. EMRP research has developed and validated a software driven Josephson Bridge that can automatically set impedance ratios, allowing multiple ratios to be achieved rapidly with a single instrument.

## Developing next-generation SI voltage standards

Quantum devices based on superconducting Josephson junctions can create small but highly reliable voltage outputs. These have great potential for use as future industrial voltage standards provided they can be scaled up and used to calibrate transfer devices that operate at room temperature.

EMRP research has demonstrated the feasibility of using Josephson junctions as a precise SI linked calibration standard that matches industrial requirements. For the first time, a prototype voltage standard, based on multiple arrays that each contain thousands of junctions, has been assembled into a single unit capable of producing the 1 volt standard required by many sensing, electronics and communications applications.

## Innovation in sub-nanometre dimension accuracy

Advanced analytical instruments, such as Atomic Force Microscopes and Scanning Electron Microscopes, are being used to make nanoscale dimension measurements, but their users need improved calibration standards to have confidence in the measurements made. Existing standards, based on precisely machined blocks of material to form nano-sized steps, is a time-consuming process that produces standards down to only 6 nm. EMRP research has successfully created silicon lattices with reproducible step height and lateral features that demonstrate the feasibility of using crystal lattices for sub-nanometre dimensional measurements. Further evaluation of this new capability is needed to ensure its international acceptance and to enable this type of standard to be used in nanoscale dimension measurements.



# EMRP SI Broader Scope II projects at a glance



Pooling expertise of

**20** NMIs  
and  
**14** DIs from  
**20** European countries



plus the NMI from  
**South Korea,**  
**Brazil,**  
**New Zealand,**  
**Japan** and the  
**Ukraine**

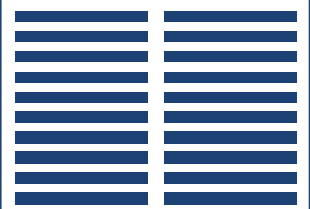


**businesses**



**28**

**published newsletters**  
**and press releases**



**108** presentations  
at workshops  
and seminars, reaching  
an audience of  
**4,500**  
people





159

articles  
in peer-reviewed  
journals



training courses  
delivered to over

560  
people

572

presentations at  
conferences



93

contributions  
to

42

technical  
committees and  
working groups  
of standards  
organisations



Supported the  
development of improved  
instrumentation with  
projected sales of

€6 M

18

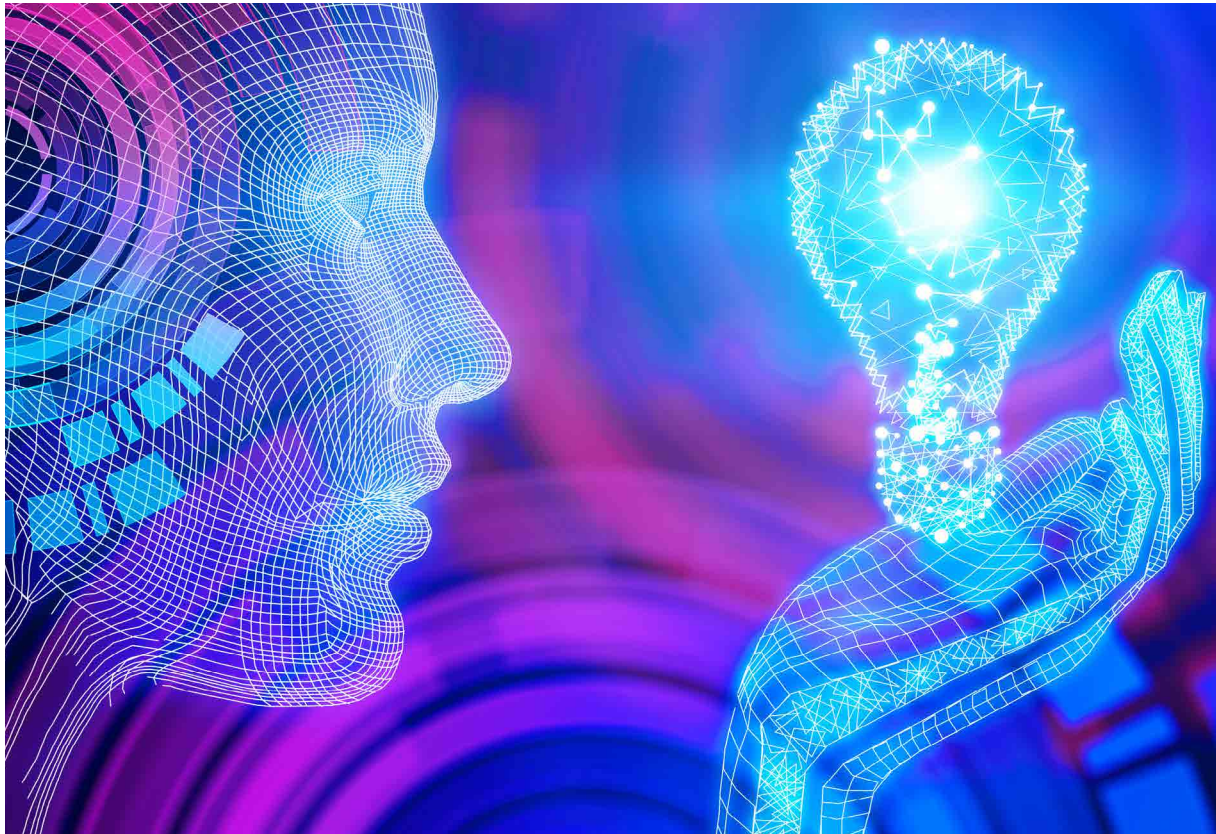
number of  
articles in  
trade and  
popular press



16

contributions to draft standards  
and published standards

# Future proofing the SI units for communications and electronics



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## Measurement challenges

Rapid advances and faster operating speeds in the electronics that are used in mobile communications, sophisticated medical instruments and advanced sensing applications, have outpaced developments in the technologies used to confirm their performance. Ensuring electronic components are reliable relies on robust measurements with rigorous links to the SI unit realisations performed at NMIs and DIs. These practical experiments must develop improved precision to keep up with technical advances.

Resistance and impedance, measured in ohms, underpin the performance of both alternating current (AC) and direct current (DC) electrical circuits. For alternating current inputs, current and voltage switch direction many times per second, creating a repeating cycle that requires accurate measurements to confirm both the frequency of the change and its magnitude in volts. Another SI unit important in micro-electronics where minuscule components need nano-precision placement, is the metre. New smaller scale dimension reference standards are needed to confirm that a component is in its correct location.

Calibration methods and reference standards confirm the performance of instruments used in industry to greater accuracy than that required in their routine use. To ensure this remains the case in the electronics sector, greater accuracy for the entire calibration chain, from the end user to the physical SI unit experimental set-up at an NMI, is needed.

EMRP research has supported projects that address:

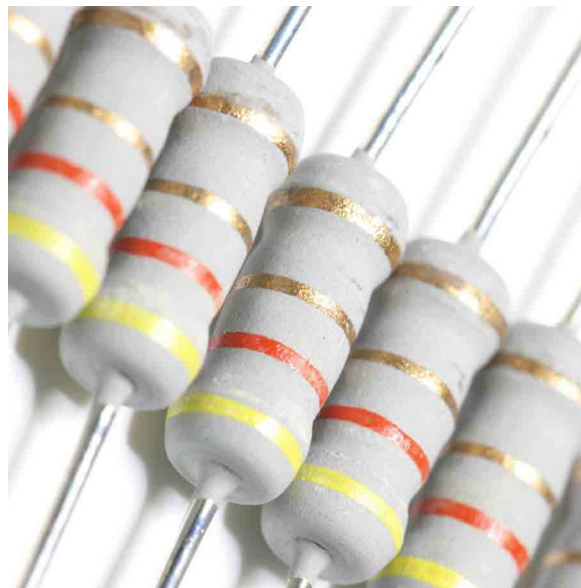
- Graphene innovation in resistance standards
- Impedance standards for next-generation electronics
- Innovation in quantum voltage standards
- Optical clocks for International timescales
- Precision for sub-nanometre measurements.

# Key technical achievements

## Graphene innovation for resistance standards

Resistors are used to manage the current flow in many electrical systems, whilst accurate resistance measurements underpin the precise control needed for sophisticated electronics and sensors. Highly accurate NMI resistance standards based on the Quantum Hall Effect (QHE) are used to link industrial instruments that characterise electronic components to the Ohm - the SI unit of resistance.

When electrical current passes through a magnetic field at right angles to the current's flow a voltage difference is generated across the conductor. This is called the Hall Effect. In very high magnetic fields and at extremely low temperatures, two dimensional structures produce the quantum version of the Hall Effect. Two-dimensional graphene has the potential to simplify the experimental conditions needed by today's NMI QHE standards. New methods for manufacturing suitable graphene, and ways to reliably characterise its performance are required before graphene can be considered for precise NMI resistance standards.



The EMRP project, **Quantum resistance metrology based on graphene**, investigated the use of graphene to create more practical resistance standards.

The Project:

- **Developed methods for fabricating graphene suitable for use as a resistance standard**, by growing graphene films on a substrate, and developed approaches to confirm its quality
- **Confirmed graphene produced the QHE at higher temperatures and lower magnetic fields than existing resistance standard materials**, whilst also identifying the further work needed to improve flow of electrons
- **Demonstrated the potential for using graphene for impedance standards**, the equivalent to resistance for AC current, which can confirm the performance of AC sensors and electronics such as touch screens
- **Developed a room temperature instrument for scaling QHE resistance values**, providing an alternative to cryogenic current comparators which rely on liquid helium to create very low temperatures.

As a result of this project, more European NMIs can now fabricate resistance grade graphene, and easier to use resistance standards have been developed. These are increasing the availability of highly precise resistance calibrations across the EU. Shortening the resistance calibration chain and bringing high quality resistance standards closer to industrial users will help innovation in electronic devices and supports increased competitiveness.

The project's manufacturing method for high-quality large-area graphene wafers is proving valuable for developing new graphene technologies, such as sensors for small magnetic fields, as well as those for radiation and gas detection.

Simpler resistance standards, and in the future potential impedance standards, will spur innovation in a wide range of technologies where the electrical resistance of materials is important, including sensors, electronics and communications.

<b>More information is available at</b>	SIB51 Quantum resistance metrology based on graphene (GraphOhm) <a href="http://www.euramet.org/project-SIB51">http://www.euramet.org/project-SIB51</a> Follow-on project: Graphene Impedance Quantum Standard (18SIB07 GIQS)
<b>Contact</b>	EURAMET MSU Office <a href="mailto:msu@npl.co.uk">msu@npl.co.uk</a>

## Impedance for next-generation electronics

Precise measurement of impedance – the resistance a circuit presents to an AC current – is vital to modern electronics. Uses include providing touch responses from smartphone screens, accurate measurements in radiation dosimeters and fuel gauges, the validation of nanoscale components and the analysis of energy loss in transmission lines.

Impedance values are defined using the Quantum Hall Effect, which can be scaled-up with pre-set transformers to create a range of impedance standards. These are all at fixed ratios, e.g. 1:2, 1:5, governed by the number of windings in the transformers used.

As electronics gain sophistication, increased measurement precision is needed. Users want calibrations for their impedance measurement instruments at intermediate values rather than at the fixed steps that are currently available, with robust links to SI units. Josephson bridges, superconducting devices that can compare two impedances, have the potential to address this issue.

The EMRP project, **Automated Impedance Metrology extending the quantum toolbox for electricity**, developed and validated Josephson and digital bridges as a simpler method for calibrating impedance standards for a wider range of values.

The project:

- **Developed and validated a software driven Josephson bridge that can automatically set impedance ratios**, allowing multiple impedance ratios to be achieved with a single instrument
- **Developed electrical signal sources for verifying bridge performance** to achieve higher levels of precision than previously possible based on modelling to determine and reduce errors
- **Developed a highly accurate fully-digital and automated voltage ratio bridge**, with an adjustment time of less than one minute that both simplifies impedance ratio comparisons and can replace the current reliance on fixed impedance transformers
- **Compared four impedance bridges using specially developed impedance standards with intermediate phase angles**, demonstrating consistency of output across different phase angles, but also highlighting further considerations for assessing bridge performance.

This project developed new impedance measurement capabilities using automated bridges. It simplified impedance measurement instrument calibrations across multiple fixed ratios, as well as allowing the use of intermediate ratios for the first time, without sacrificing accuracy. In the longer term this will speed up and simplify previously complex instrument calibrations. Project advances also now provide calibrations at lower capacitance levels than were previously possible, which is important for new nanotechnologies and touch sensitive devices that respond to very tiny impedance/capacitance changes. Commercial interest in the project's new impedance standards has been expressed by a semiconductor manufacturer that needs individual standards for low value capacitances. The improved calibrations resulting from this project will allow more accurate impedance measurement and testing, supporting innovation in the next generation of electronics and sensors.



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<p><b>More information is available at</b></p>	<p>SIB53 Automated impedance metrology extending the quantum toolbox for electricity (AIM QuTE)  <a href="http://www.euramet.org/project-SIB53">http://www.euramet.org/project-SIB53</a>            Follow-on project: A versatile electrical impedance calibration laboratory based on digital impedance bridges (17RPT04 VersICAL)</p>	
<p><b>Contact</b></p>	<p>Luis Palafox Gámir (PTB)</p>	<p><a href="mailto:luis.palafox@ptb.de">luis.palafox@ptb.de</a></p>



## A quantum voltage standard

Rapid advances and faster operating speeds in electronics, from phones to sophisticated medical instruments, have outpaced advances in the technology needed to confirm their performance. For alternating current (AC) inputs, current and voltage switch direction many times per second, creating a repeating cycle. Measurement methods use digitisation to convert the continually changing signal from this cycle into a number. This means sampling voltages at very high speed and assigning numeric values, which creates the potential for inaccurate signal transmission. Ensuring voltages are measured with precision, minimised errors and traceability to the SI is important for cutting-edge electronics.

Quantum devices based on superconducting Josephson junctions that create small but highly reliable voltage outputs have great potential for future industrial voltage standards provided they can be scaled up and used to calibrate transfer devices operating at room temperature.

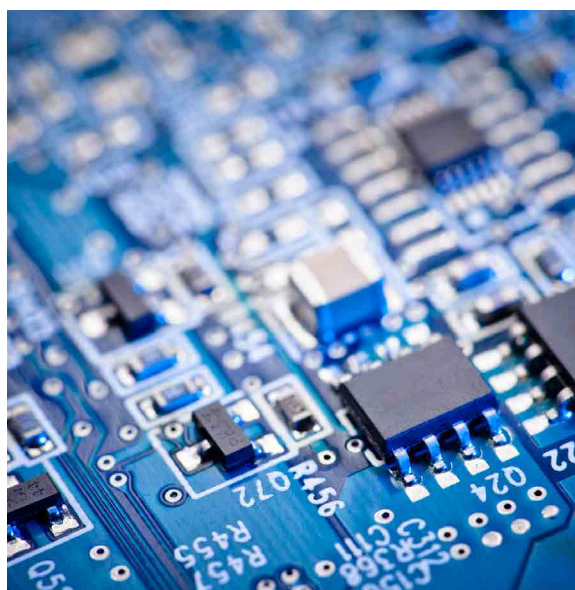
The EMRP project, **A quantum standard for sampled electrical measurements**, made significant developments in producing traceable voltage standards based on Josephson junctions and improving their accessibility to industrial users.

The project:

- **Developed the first prototype quantum voltage standard capable of producing the 1 volt output required by industry**, by optimising Josephson junctions and assembling multiple 9000 junction arrays
- **Demonstrated the feasibility of photodiodes to generate the precise currents needed to operate Josephson junctions.** Light pulses generated at room temperature are transmitted through telecom grade fibre to extremely low cryogenic temperature photodiodes to create the voltage output of the Josephson junction arrays
- **Developed and validated the performance of a world leading quantum voltage transfer standard**, the DualDAC2. This room temperature pulse waveform generator was used to compare NMI cryogenic voltage standards to ensure European harmonisation for the SI volt
- **Investigated algorithms and simulations for determining uncertainties associated with high frequency AC waveform sampling and developed a toolbox** to help industrial users to assess measurement uncertainties.

The project demonstrated the feasibility of using superconducting Josephson junctions as precise SI linked calibration standards that match industry requirements for a 1 V AC standard. The DualDAC2, which is superior to anything currently on the market for high-precision AC voltage measurements, is being commercialised by the Finnish company Aivon. This will provide a cost-effective instrument for advanced electronics manufacturers to test components against the SI derived volt, helping users to demonstrate that their components match specifications.

Development of the photodiode and optical fibre concept continues in the EMPIR project 15SIB04 QuADC, to improve accuracy further.



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<b>More information is available at</b>	SIB59 A quantum standard for sampled electrical measurements (Q-WAVE) <a href="http://www.euramet.org/project-SIB59">http://www.euramet.org/project-SIB59</a> Follow on project: Waveform metrology based on spectrally pure Josephson voltages (15SIB04 QuADC)
<b>Contact</b>	Johannes Kohlmann (PTB)      johannes.kohlmann@ptb.de

## Optical clocks for International timescales

The SI unit of time, the second, underpins international timekeeping and is relied upon by power grids, the internet, financial transactions and navigation systems. Improving the accuracy and stability of international timescales will bring more precision to many applications.

The second is currently kept constant by comparing a microwave source to a fundamental property - an absorption frequency of caesium atoms. However, a new generation of optical clocks, using higher frequency laser light, can now achieve greater accuracy and stability. For any future redefinition of the SI second based on optical clocks, the accuracy of different types of clock must be confirmed by a coordinated programme of comparisons, and their frequencies robustly linked to existing caesium standards.

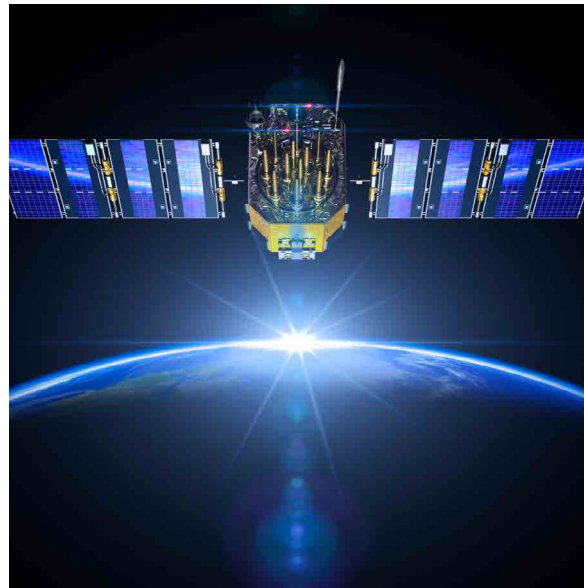
The EMRP project, **International timescales with optical clocks**, tackled these and other important considerations for a redefinition of the second using optical frequency clocks.

The Project:

- **Performed a comparison of different types of optical clocks**, within and between institutes, establishing ratios between their operating frequencies and relating them to the caesium standard
- **Investigated enhanced satellite techniques for comparing the frequencies of clocks in remote locations**, and found that advanced processing of comparison data from GNSS satellites was comparable in performance to using dedicated satellite transponders, but far cheaper
- **Measured the Earth's gravity potential with improved precision at four European NMIs**, which will enable the operating frequencies of the optical clocks to be corrected for gravitational effects when contributing to international timescales
- **Developed a transportable optical clock** and used it to measure the gravity potential in the middle of a mountain, demonstrating a future application of the new technology.

Robust procedures, developed by this project, for analysing the self-consistency of clock comparison data and deriving optimised values for the frequencies of the optical clocks will allow them to be integrated into international timescales, immediately improving their stability. The work will also enable better informed decisions to be taken on any future redefinition of the second.

The international scientific community will also benefit from validated optical clock performance when conducting tests of fundamental physical theories. Early beneficiaries will include the European Space Agency (ESA) and the European Very Long Baseline Interferometry Network (EVN), who have facilities requiring accurate time and frequency signals. Measurements of gravity potential differences using optical clocks will be important in geodesy, for example, in monitoring the effects of climate change on sea levels.

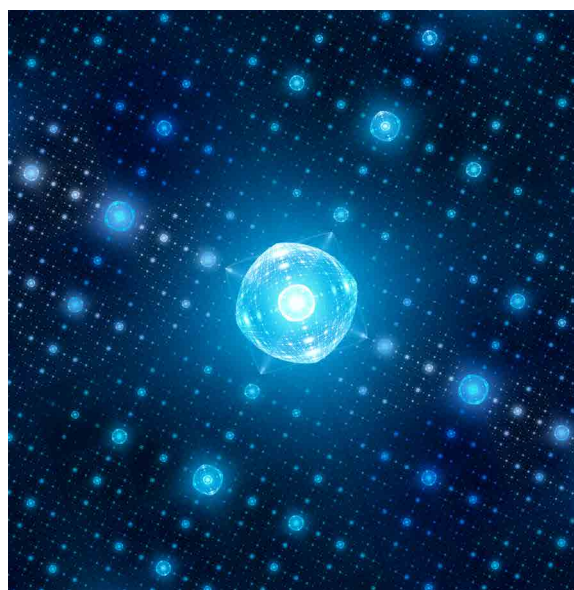


courtesy ESA

<b>More information is available at</b>	SIB55, International timescales with optical clocks (ITOC) <a href="http://www.euramet.org/project-SIB55">http://www.euramet.org/project-SIB55</a> Follow-on project: Robust Optical Clocks for International Timescales (18SIB05 ROCIT)	
<b>Contact</b>	Helen Margolis (NPL)	helen.margolis@npl.co.uk

## Accuracy for the ‘short distance’ metre

The global market for advanced electronics is currently valued at around €235 bn, with semiconductors being key manufacturing materials. The EU has a goal of supplying 20 % of all silicon wafer production by 2025. The ability to make accurate nanoscale measurements during the manufacturing process is an important factor for reliable production. Instrumentation, such as Atomic Force Microscopy is used to assess production quality, but currently few nanometre dimensional standards exist to confirm performance. The natural shapes of crystals, polymer chains or DNA folded into pre-determined shapes all have great potential to self-organise into repeatable and reproducible structures for use as nanoscale rulers. Before these can be routinely used, further investigations are required to confirm their suitability for characterising advanced measurement techniques.



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The EMRP project **Crystalline surfaces, self-assembled structures, and nano-origami as length standards in (nano)metrology**, developed novel dimensional reference standards, based on self-organising crystalline and molecular structures, for the calibration of the instruments that are used to measure the dimensions of advanced nanoscale electronic components.

The project:

- **Developed prototype nano-dimensional standards based on silicon crystals**, which form regular lateral and step height features, for use in the calibration of scanning microscopes
- **Developed prototype nanoscale standards based on the self-assembly of polymer structures** to produce repeatable lateral grids - patent application
- **Developed so-called “find-me” structures** to aid users in identifying the locations of features on reference standards
- **Demonstrated the feasibility of using “nano-origami”** to manipulate DNA to produce repeatable structures that are suitable for future use as dimensional standards.

This project investigated self-organised, repeatable structures formed from silicon crystal lattices, polymer chains or DNA sequences for use as nano-dimensional standards, with patent applications already registered to protect IP. Although 20 times smaller than previously available reference materials, these prototypes have 10 times better accuracy. The Comité International des Poids et Mésures (CIPM) is considering the adoption of these new reference materials to calibrate instrumentation for measurements at the nanoscale. Further comparison studies between National Measurement Institutes are needed to demonstrate to the BIPM the reliability of procedures for their production and characterisation. Then the introduction of international standards and best practice guidance to increase measurement uniformity and accuracy at the nanoscale are required before these reference length standards based on the fundamental properties of nature, can be introduced to help maintain European competitiveness in advanced electronics manufacturing.

<b>More information is available at</b>	SIB61 Crystalline surfaces, self-assembled structures, and nano-origami as length standards in (nano)metrology (Crystal) <a href="http://www.euramet.org/project-SIB61">http://www.euramet.org/project-SIB61</a>	
<b>Contact</b>	Ingo Busch (PTB)	ingo.busch@ptb.de



# Improved links to the SI units for specific applications



## Measurement challenges

Industrial production processes and manufacturing quality assessments rely on a rigorous calibration chain from the measurement instrumentation used to the top level SI unit realisations performed at NMIs. Ensuring that this chain meets user requirements relies on measurement research to develop and expand existing capabilities to meet increasing and specific individual industrial accuracy demands.

Each specific manufacturing process has its own requirements, not all of which can be met by a single calibration to SI unit realisations. Components assembled into complex systems must frequently undergo acceptance testing to ensure manufacturing specifications have been met, and once assembled into systems or devices, the final product will perform as anticipated. Sometimes this testing is performed at the limits of measurement capability, as in the case of the acceptance testing of complex optical components used in high intensity beam lines for fundamental material research. Radio frequency components for advanced electronic applications must also demonstrate stringent conformance to specification sheets or new circuits will not work as designed. More bespoke measurement instrumentation calibrations may be needed to meet the exacting requirements of specific user communities.

EMRP research has supported projects that address specific industrial user requirements for increased calibration accuracy with improved links to the SI units. Projects have increased the accuracy of calibrations for:

- Angle measurement instrumentation important for assessing complex optic quality and also confirming robotic machine tool movement precision
- GNSS based surveying instrumentation and other technologies important in the construction industry
- Instruments used to confirm that radio frequency component performance matches specifications important in communication technologies
- In-process moisture measurement instruments important for production quality.

# Key technical achievements

## Precision for the 'long distance' metre

Large construction projects such as building tunnels and bridges must often be delivered with millimetre accuracy. Similarly, mountain towns, mines, and nuclear sites need to be closely monitored for tiny movements that may lead to landslides or sinkholes. Long distance measurements are made using both global navigation satellite systems (GNSS) and electronic distance measuring (EDM) Instruments, with European products contributing over €107M to the EU's economy annually.

EDMs use laser-based ranging systems calibrated against baseline networks consisting of a series of well-defined pillars, but temperature and air turbulence change the air's refractive index, reducing calibration and measurement accuracy. GNSS is influenced by high atmospheric environmental factors as well as by electromagnetic near-field effects. To improve long distance measurement precision, better links to the SI definition of the metre with sub-millimetre uncertainties are needed.

The EMRP project, **Metrology for long distance surveying**, developed new robust calibration and transfer standards with compensation for refractive index changes, and made recommendations to improve measurement practices.

The Project:

- **Developed the TeleYAG, which uses interferometry to perform in-situ compensation for refraction variations**, achieving sub-millimetre accuracy over distances of up to a kilometre, and creating traceability to the SI meter without reference baselines or environmental sensors
- **Developed and validated the single laser TeleDiode system capable of achieving a measurement resolution below 5 µm over 1 km**. This system has the potential to create a cost effective and robust standard for transferring accuracy between base stations and user instruments
- **Extended the distance measurement capability of highly accurate multi-wavelength femtosecond ranging from 15 cm to 50 m**, using femtosecond combs, which create a direct link between short femtosecond frequencies and longer frequencies for metre-scale measurements
- **Investigated sources of inaccuracy for GNSS systems**, associated with satellite positioning, signal propagation and measurement antenna position, and suggested improvements.

This project developed solutions for high accuracy long distance measurement enabling better traceability for surveying, geodesy and earth sciences. The TeleYAG and TeleDiode now serve as standards for long distance measurements, with the TeleDiode being commercialised and having additional potential for use in large volume measurements, building on developments from the EMRP LUMINAR (IND53) project. Best practice for both GNSS and EDM surveying instruments was publicised by the German Society for Geodesy, Geoinformation and Land Management, in both German and English to promote uptake by the international surveying community.

Increased interaction between the metrology and geodesy communities, as a result of this project, has enabled a member of the consortium to join and chair an influential geodesy organisation, the International Earth Rotation and Reference Systems Service Working Group on Site Survey and Co-location.



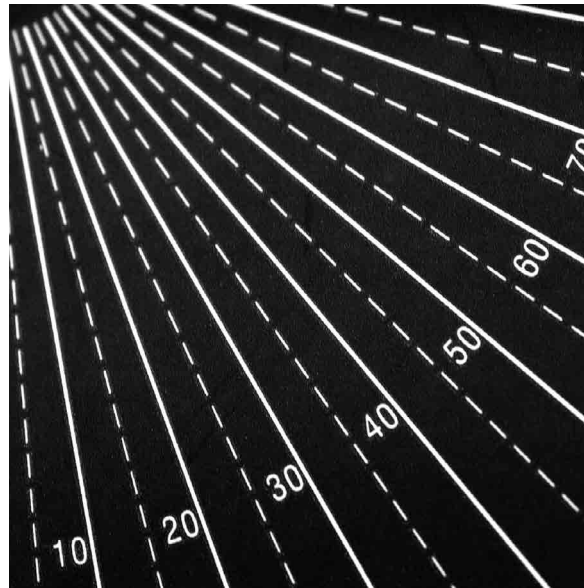
© stock\_colors

<b>More information is available at</b>	SIB60 Metrology for long distance surveying (Surveying) <a href="http://www.euramet.org/project-SIB60">http://www.euramet.org/project-SIB60</a>
<b>Contact</b>	Florian Pollinger (PTB)      florian.pollinger@ptb.de

## Angle metrology

Precise angle measurements, made using optical systems, underpin both important European industries and also fundamental research facilities that operate focused high intensity infrared, ultraviolet and X-ray beams. In the automotive, aerospace and mechanical engineering sectors robotic machines welding tools in 3D rely on the precise control of rotating shafts by angle encoders calibrated using optical techniques.

At synchrotron and free electron laser (FEL) facilities complex optical systems probe the structure and properties of candidate materials for advanced applications such as next-generation solar panel films, new pharmaceuticals or creating a greater understanding of ultra-fast processes in catalysis. These optical systems operate at the limits of existing manufacturing and measurement capability. Nearly 30 % of system components fail exacting acceptance testing as any imperfections larger than 1 nm create optical distortions that affect research results. Autocollimators measure the angular displacement of reflecting surfaces and are frequently used to identify nanoscale irregularities in complex optic components. Improving the accuracy with which these instruments can measure tiny defects will help to ensure that beamlines operate as designed.



The EMRP project, **Angle metrology**, improved calibration and reduced sources of uncertainty with a particular focus on the optical systems that are used for focusing and conditioning high intensity x-ray beams.

The project:

- **Improved autocollimator performance** by introducing calibrations along two axes, which is to in-service use, and also by creating novel image patterns on an autocollimator's detector
- **Developed a new centring device, ACenD, for precisely positioning small apertures on the autocollimator's optical axis.** This enables the identification of smaller irregularities than was previously possible
- **Investigated factors affecting the performance of angle encoders and applied a new shearing technique** to improve the calibration of precise angle measurement devices
- **Developed small angle generators capable of operating over a wide range** for the on-site/in-situ calibration of the autocollimators that are used in surface profilers to improve inspection accuracy of complex optical surfaces.

Project developments are aiding acceptance testing of the most complex optical components that are used in advanced large-scale photon science research centres. Feedback on optics performance helps manufacturers improve products and eliminate errors and helps ensure that beam lines operate as expected for dedicated research and testing. As a result of this project, two EURAMET guides on the calibration of angle encoders and autocollimators have been published to support laboratories at research facilities and national institutes.

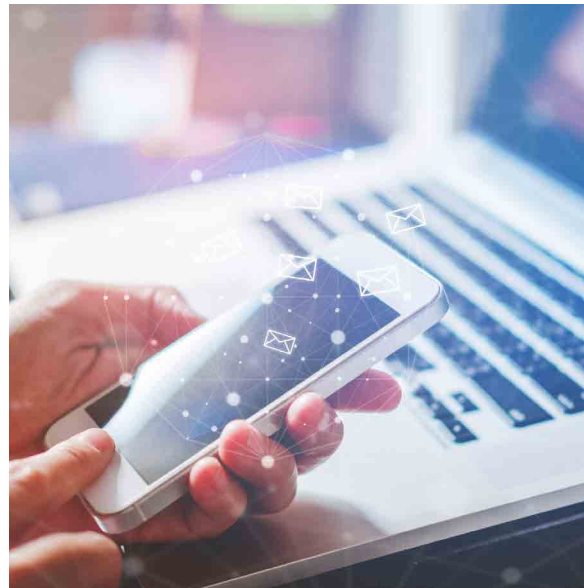
This project's outcomes have future applications in many areas of advanced manufacturing which use angle measuring technologies to confirm robotic machine tool or nano-scale component positioning. These will also have applications in geodesy and nano-electronics research.

<b>More information is available at</b>	SIB58 Angle metrology (Angles) <a href="http://www.euramet.org/project-SIB58">http://www.euramet.org/project-SIB58</a>
<b>Contact</b>	Tanfer Yandayan (TUBITAK)      tanfer.yandayan@tubitak.gov.tr

## Greater accuracy for high-frequency circuits

From laptops and smartphones to security scanning and medical diagnostics, many devices now require radio-frequency (RF) electronic circuits to operate. As demand for higher data rates grows, existing RF systems and devices incorporating new materials (graphene, for example) need testing at ever higher performance levels. The vector network analyser (VNA) is the key instrument used to assess RF systems and components such as the waveguides that are used for signal transmission. To achieve the higher measurement accuracies needed by industry, new and improved calibration methods are required which are traceable to the SI units.

The EMRP project **Metrology for new electrical measurement quantities in high frequency circuits**, developed traceable calibration methods for RF electronics measurements, including hardware for the characterisation of VNAs, waveguides, non-linear amplifiers in 5G communications, and RF components with “extreme” impedances (based on new materials such as graphene).



© undefined undefined

The project developed:

- **Traceable test methods and reference devices** to characterise the high frequency waveguides that are used for signal transmission in electronic devices
- **A reference printed circuit board (PCB)** to enable the removal of testing contributions from assessments of electronic circuits. This demonstrated the feasibility of PCB integration into other circuitry for built-in, ongoing device performance monitoring
- **A reference device enabling large-signal distortions to be quantified during high-power transmissions**, which is important during 5G communication amplifier prototyping.

This project has successfully developed calibration methods and reference devices to help meet the current and emerging requirements of radio frequency (RF) device manufacturers. The project’s VNA calibration methods and best practice information have been incorporated into a recent revision of the EURAMET Calibration Guidelines No 12. To address problems caused by poor component compatibility, the project investigated connection sizing issues and results from these studies have contributed to a new series of IEEE standards (the 1785 series).

These are significant steps towards the introduction of greater measurement harmonisation in RF electronics. Newly available measurement services for the traceable calibration of RF transmission components (coaxial lines and waveguides) will also support developing RF technologies such as 5G communications. Building on these achievements, further EMPIR funding was subsequently secured for the follow-on projects 14IND10 *Metrology for 5G communications* (MET5G), and 14IND02 *Microwave measurements for planar circuits and components* (PlanarCal).

<p><b>More information is available at</b></p>	<p>SIB62 Metrology for new electrical measurement quantities in high frequency circuits (HF Circuits)  <a href="http://www.euramet.org/project-SIB62">http://www.euramet.org/project-SIB62</a>            Follow on projects: Metrology for 5G communications (14IND10 MET5G)            Microwave measurements for planar circuits and components (14IND02 PlanarCal)</p>	
<p><b>Contact</b></p>	<p>Nick Ridler (NPL)</p>	<p><a href="mailto:nick.ridler@npl.co.uk">nick.ridler@npl.co.uk</a></p>



## Moisture measurements in materials

Moisture content affects performance, lifespan, processing speed, weight and the price of almost all manufactured products, including paper, food, fuels, pharmaceuticals, glues and coatings. The quality of many industrial products relies on controlling or removing moisture at the end of the production process.

During the production process moisture analysers are used to determine how much water is present in a material or product. These analysers are calibrated through comparison with the 'loss on drying' technique, which measures how much of the sample's water volume is evaporated at a controlled temperature. This technique lacks traceability due to the uncertainty around how well moisture is extracted by the evaporation process and how much is from other extracted volatile materials. Increased accuracy and improved links to the SI units will provide industry with the robust measurements required for the quality control of moisture content.



© dimage

The EMRP project, **METefnet Metrology for Moisture in Materials**, developed new techniques and reference materials to improve traceability to SI units and the transferral of this to industrial moisture measurements nearer to the production process.

The Project:

- **Developed four highly accurate reference methods**, one using chemical analysis (titration) and three based on measuring water vapour removal from a sample by drying and validating them through comparison exercises
- **Developed well-defined reference materials**, with confirmed homogeneity, stability and lifespan, in order to transfer traceability from NMIs to calibration laboratories
- **Developed a model for predicting how water is absorbed and transported through materials**, which could be used to improve product performance, particularly for glues and coatings
- **Developed a novel calibration system, using DRIFT spectrometry, in order to transfer traceability to surface moisture measurement probes.** This system measures moisture content based on the changing reflectance of infra-red light.

This collaborative project brought together a diverse range of moisture and temperature experts to tackle a lack of traceability and fragmented knowledge in this area across the EU, raising understanding and capabilities across the board. The improved processes developed by the project are now available as two best practice guides on making reliable calibrations, one on titration uncertainty and one on sample handling and transportation uncertainty.

Research into moisture in different materials is also having a direct benefit in various industrial sectors. Biofuels companies can now better determine the water content of wood pellets enabling greater combustion efficiency, coupled with reduced CO<sub>2</sub> emissions. Agricultural production requires knowledge of soil moisture based on reliable measurements to optimise irrigation for increased crop yields. A follow-on project will link the project's primary measurement techniques to soil measurement instruments.

<b>More information is available at</b>	SIB64 Metrology for moisture in materials (METefnet) <a href="http://www.euramet.org/project-SIB64">http://www.euramet.org/project-SIB64</a>
<b>Contact</b>	Martti Heinonen (VTT) <a href="mailto:martti.heinonen@vtt.fi">martti.heinonen@vtt.fi</a>

# Improving standardisation and the demonstration of regulatory compliance



## Measurement challenges

Measurements are linked to NMI maintained SI units via a calibration chain that frequently uses independent test laboratories as intermediaries that perform calibrations to international normative documentary standards. Standards issued by CEN/CENELEC - the European standards organisation – that carry the European Normative (EN) designation automatically replacing national standards in all EU member states. This ensures harmonisation of the measurement infrastructure across the EU and assists an organisation's ability to demonstrate regulatory compliance.

Accreditation schemes provide confidence in the quality of the calibration certificates issued by test laboratories and underpin the European CE quality mark that gives consumers confidence in a product's performance. To demonstrate the equivalence and quality of their memberships measurements, accreditation schemes operate proficiency test exercises in which labs are sent well characterised materials for evaluation and results are compared to help raise measurement quality.

To meet the changing demands of users, research is needed to investigate measurement technique improvements and to produce new certified reference materials. EMRP research has supported projects that will enable user communities to:

- Introduce greater standardisation for disease diagnosis methods that use cells and biomolecules
- Introduce new documentary standards for light intensity measurements for energy efficient light sources
- Demonstrate the compliance of sound power assessments of noise sources with EU directives
- Demonstrate the compliance of industrial insulation materials with EU construction regulations
- Demonstrate that construction materials meet high load safety testing.

# Key technical achievements

## Standardising disease diagnoses using cells and biomolecules

Many medical diagnosis techniques, such as those for identifying heart attack risk or detecting cancer, depend on accurately determining the amount of DNA, proteins and cells in biological samples. Improved diagnoses lead to earlier interventions and improved treatment monitoring.



Courtesy LGC

Diagnostics based on polymerase chain reaction (PCR) including next generation sequencing (NGS) amplify trace amounts of mutated DNA, enabling them to be measured within complex biological samples. But these, and other clinical methods that are used to measure lipoprotein levels and to count cells, lack traceable reference methods and materials. This leads to inconsistent results across different laboratories and means that borderline cases can be missed. It also makes it difficult to gather the quality of data needed for new medical device regulations. Recent developments using techniques based on biomolecular and cell counting require rigorous characterisation to establish SI traceability and to demonstrate their reproducibility when performed in different laboratories.

The EMRP project, **Traceability for biologically relevant molecules and entities**, demonstrated for the first time, the potential for achieving SI traceability through determining the basis for clinical reference measurement procedures to support comparability in critical healthcare measurements.

The project:

- **Established digital PCR (dPCR) as a primary reference measurement procedure for DNA copy number quantification**, through comprehensive evaluation of sources of error and comparison with mass spectrometry measurements. This was successfully applied to improve the accuracy of a clinical study on cancer biomarker diagnostics
- **Developed a new application of electrospray-differential mobility analysis (ES-DMA)** for analysing lipoprotein particle sizes in blood, which are associated with cholesterol levels that create cardiovascular disease risks
- **Improved SI links for impedance counting flow cytometry**, which is used to count individual particles, linking electrical charge to cell size to enable its use for comparing cell measurement instruments
- **Applied NGS as a novel method for the assessment of DNA** reference material purity and defined limits for the quantification of minority sequences impurities.

This project has made a significant contribution to the growing global movement, led by the Joint Committee for Traceability in Laboratory Medicine (JCTLM), for greater assay standardisation and global harmonisation in the clinical laboratory measurement community. A European Metrology Network is being formed to address the needs of stakeholders in this area of medical science. The project's highly precise reference method for a cancer genetic marker, the first for nucleic acids, has been added to the JCTLM database, and project results improving SI traceability through biomolecular counting have contributed to the revision of ISO 17511 – a key standard for increasing measurement harmonisation in healthcare. Other project inputs to normative standards include quality criteria for dPCR and NGS and flow cytometry advances, whilst a new working group, instigated by the International Federation of Clinical Chemistry, is pursuing project advances on the improvement of routine cholesterol measurements.

<b>More information is available at</b>	SIB54 Traceability for biologically relevant molecules and entities (Bio-SITrace) <a href="http://www.euramet.org/project-SIB54">http://www.euramet.org/project-SIB54</a>
<b>Contact</b>	Helen Parkes (LGC) <a href="mailto:helen.parkes@lgcgroup.com">helen.parkes@lgcgroup.com</a>



## Improving SI links for light intensity measurements

Europe is world leading in low energy lighting and optical technologies for communications, healthcare and security, and it makes 30 % of all light measurement devices in a total global market worth €23 billion.

Standards for light measurement, which were developed for incandescent lighting, use radiometers to measure radiant power to link it to the SI unit of luminous intensity – the candela. Radiometers converting light into electrical power are complex to use and operate at very low temperatures. As light generation technologies develop, new accurate standards are needed for determining the intensity of different light sources, with robust links to the candela, to enable industrial calibration labs to make reliable measurements.

The EMRP project, **New primary standards and traceability for radiometry**, developed two new

primary standards for radiometry, one that operates at cryogenic temperatures with very high accuracy, and another for use at room temperature that can, for the first time, be easily used by calibration and testing laboratories.

The project:

- **Developed silicon photodiodes**, which emit a voltage in response to light. These were implemented into two predictable quantum efficiency detector (PQED) devices: a highly accurate low temperature version and a room temperature version
- **Increased the accuracy of existing cryogenic radiometers** and used these to validate the cryogenic PQED, confirming very low uncertainties and its suitability for comparing light measurement devices to the candela
- **Developed a room temperature variant of the PQED**, optimised its performance and validated it against the candela through comparisons to the cryostat version
- **Used the room temperature PQED to calibrate commonly used industrial sensors** with values agreeing to within the 100 ppm uncertainty goal, significantly shortening the traceability chain to the Candela for such devices.

This project enables calibration and testing laboratories, and the industries they serve, to benefit from new light sensor detectors and techniques by providing reliable calibrations with robust links to the SI Candela. The PQED has been accepted, alongside the cryogenic radiometer, as a method to directly compare light measurement instruments to the candela with very low uncertainties. Room temperature PQEDs were shown to be suitable for use in industrial labs with accuracy requirements at the 100 ppm level. A patent application has been filed for the novel photodiodes that were developed in the project which will be commercialised by the newly formed Finnish company, ElFys Oy.

Project research will help the European photo-sensor industry grow its global lead, as applications expand into new areas such as advanced diagnostic devices, healthcare treatments, and smart imaging. This in turn supports Europe's lighting and optical industries, improving quality control for innovative optical technologies.



© Pupkis

<b>More information is available at</b>	SIB57 New primary standards and traceability for radiometry (NEWSTAR) <a href="http://www.euramet.org/project-SIB57">http://www.euramet.org/project-SIB57</a>
<b>Contact</b>	Maria Luisa Rastello (INRIM) <a href="mailto:m.rastello@inrim.it">m.rastello@inrim.it</a>

## Real world sound measurements

Domestic appliances and industrial machinery must meet EU Directives that limit the noise they produce in order to protect the hearing of European citizens. A range of regulations require manufacturers to declare sound power levels from domestic appliances such as vacuum cleaners, or power tools in order to ensure public safety.

Assessments of sound power, which is measured in watts - the SI derived unit of power - are routinely made using microphones in a specially designed environment where no sound is reflected. This is known as a free field. In the real world, echoes from walls or objects can amplify noise beyond safety limits, and machinery verified in a lab may fail noise tests in use. Sound power calibrations that consider environmental reverberations to ensure better regulatory compliance require investigation to ensure accuracy before any changes to current practice can be made.



Courtesy PTB

The EMRP project **Realisation, dissemination and application of the unit watt in airborne sound**, investigated calibration methods which reflect environmental effects on sound measurements and proposed that a significant change to existing calibration methods should be adopted.

The project:

- **Modelled, designed and constructed new precise sound power sources** by creating highly controlled vibrations for use in performing sound power calibrations
- **Evaluated these power sources to determine measurement uncertainties and developed corrections**, using rooms designed to absorb or reflect sound in a predictable way, and suggested ways to characterise sources using only free-fields
- **Characterised commercial sound power standards, based on rotating fan blades**, by linking sound power levels to the extremely accurate standards used in NMIs, and developed a calibration procedure for this type of standard
- **Established that the test environment and the procedures used introduce systematic differences between measurement methods**. This was established using everyday sources of sound including vacuum cleaners, compressors, and angle grinders.

This project has increased our understanding of how sound power levels deviate depending on the environment and improved NMI capabilities to measure sound power. As a result, a complete change in measurement philosophy based on free-field characterisation is being proposed. A formal comparison of sound power measurement methods has been arranged as a first step towards developing equivalence between NMI sound power measurements and the introduction of calibration services. The STandardization, Innovation and Research (STAIR) Working Group is considering the project's results with a view to proposing the additional measurement research needed to establish a new EU standard on sound insulation measurements at low frequencies where sound insulation is defined as a sound power ratio. Outputs have also been incorporated into the ISO3744 revision to support the determination of measurement uncertainties and to improve traceability for low frequency sounds.

<b>More information is available at</b>	SIB56 Realisation, dissemination and application of the unit watt in airborne sound (SoundPWR) <a href="http://www.euramet.org/SIB56">http://www.euramet.org/SIB56</a>	
<b>Contact</b>	Volker Wittstock (PTB)	<a href="mailto:volker.wittstock@ptb.de">volker.wittstock@ptb.de</a>

## Meeting EU regulations on thermal insulation

Thermal insulation materials are essential for protecting plant or processes from high temperatures which is important in industries from steel, glass and petrochemical production to air transport. For example, in the petrochemicals sector, European refineries could increase turnover by €3.5 billion/year through using improved insulation.

Advanced thermal insulators are thinner, stronger and lighter than more conventional products, but these require rigorous characterisation before plant designers can use them. Accurate measurements with robust links to SI units are required for testing at higher temperatures than is currently possible in order to produce reliable the reliable and comparable thermal performance specifications that underpin the use of industrial thermal insulation.

The EMRP project **Metrology for thermal protection materials**, investigated the commonly used “guarded hot plate” method for determining thermal conductivity, extending its traceability to 650 °C.



© artas

The Project:

- **Investigated the performance of materials and sensors used in high-temperature guarded hot plates** in order to gain an understanding of usage requirements for use to 850 °C
- **Investigated and reduced significant measurement errors** due to sample distortion caused by sample bowing during testing, by modelling hot plate-sample interactions
- **Characterised high-density calcium silicate for use as the first reliable high temperature insulation reference material**
- **Demonstrated improved measurement agreement between the project partners and a major industrial test lab** with greater accuracy than was previously possible. This established robust links between the SI units and industrial testing labs for the first time.

This project has successfully enabled European National Measurement Institutes (NMIs) to improve the accuracy and SI traceability of thermal conductivity measurements, and to extend their testing capabilities to higher temperatures. By proposing changes to measurement procedures, the project has been able to reduce the effects of common sources of measurement result variation leading to greater uniformity in the insulation test data that is produced in different laboratories. Rolling out improved measurement accuracy to industrial testing labs via accreditation schemes supports user confidence in the performance certificates required to underpin the insulation product data sheets and the awarding of the CE quality mark.

The optimal use of thermal insulation in industrial engineering will provide benefits such as improved structural integrity, greater safety, and greater energy efficiency coupled with reduced CO<sub>2</sub> emission. As a result of this project, more accurate characterisation of thermal insulations will give designers and engineers increased confidence when choosing appropriate insulation materials in order to meet product or plant design specifications.

<b>More information is available at</b>	SIB52 Metrology for thermal protection materials (Thermo) <a href="http://www.euramet.org/project-SIB52">http://www.euramet.org/project-SIB52</a>
<b>Contact</b>	Jiyu Wu (NPL) <a href="mailto:jiyu.wu@npl.co.uk">jiyu.wu@npl.co.uk</a>

## Better high force measurements for industry

Large-scale structures, from high-rise buildings to bridges and wind turbines, must often withstand considerable loads. EU directives require that structures remain safe under all conditions and that construction materials are tested to confirm safety margins. Large material testing machines able to produce the high loads experienced by structures rely on transfer standards – called build-up systems – to transfer traceability from precise lab-based calibrations to material testing facilities.

Multiple transducers, devices that convert force into an electrical signal, are commonly used to measure the loads experienced by build-up systems in such tests, but understanding their performance beyond their normal operating range requires further investigation.

The EMRP project, **Force traceability within the meganewton range**, investigated the performance of different types of build-up system components using high loads to develop new calibration procedures for complete systems to 50 MN with robust links to the SI units.



© Adam Alphan

The project:

- **Investigated differences between single transducer calibrations and their use in build-up systems** in order to enable reliable performance extrapolation to loads beyond their normal operating limits
- **Developed a calibration correction database** for transducers and build-up systems based on determining the effects of environmental conditions to improve measurement accuracy
- **Established new calibration procedures** for build-up systems to 50 MN, enabling their use as transfer devices for material testing machines in material testing facilities
- **Developed and validated a novel hexapod build-up system** with six load monitoring 'legs'. This enables test machine alignment, a major source of measurement error, to be reliably assessed for the first time.

This project investigated the performance of individual transducers and also when these are assembled into different types of build-up systems in order to generate improved calibrations with robust links to the SI units. As a result, operators of high load material testing machines can now have greater confidence in the reliability of their measurements. Improved calibrations support greater testing accuracy and help building material manufacturers to demonstrate the strength of their products which aids compliance with the European Directives that underpin public safety.

The hexapod system enables the accurate assessment of test machine alignment by identifying any forces exerted outside of the main test loading direction. For the first time it is now possible to reliably determine test machine alignment, and any changes to the load's direction induced during the testing of complex components such as rail carriage springs. Improving testing accuracy will increase confidence in spring performance testing that must meet the standards required by EU Directives.

Building on the outcomes of this project, the EMPIR project Torque measurement in the MN•m range is developing traceability for rotational force measurements above 1 meganewton metres.

<p><b>More information is available at</b></p>	<p>SIB63: Force traceability within the meganewton range (Force)  <a href="http://www.ptb.de/emrp/forcemetrology.html">http://www.ptb.de/emrp/forcemetrology.html</a>            Follow on projects: Torque measurement in the MN•m range (14IND14 MNm Torque) and Comprehensive traceability for force metrology services (18SIB08 ComTraForce)</p>	
<p><b>Contact</b></p>	<p>Rolf Kumme (PTB)</p>	<p><a href="mailto:rolf.kumme@ptb.de">rolf.kumme@ptb.de</a></p>



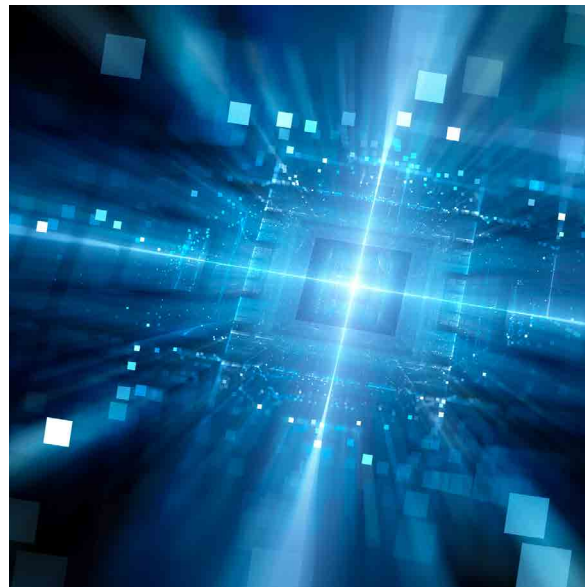
# Focus on Impact

All EMRP projects engage widely with the user communities who can benefit from their research. The second EMRP SI Broader Scope theme supported activities across a broad range of industrial sectors from ensuring public safety to increasing the use of sustainable biofuels to maintaining industrial competitiveness. All aspects of modern life rely on an advanced measurement infrastructure based on accurate calibrations with robust links to the SI units. These must be rigorously applied throughout the complete manufacturing cycle from the fundamental research underpinning the introduction of novel materials to confirming the quality of sophisticated products.

## Assessing complex optic performance

The structural properties of new materials, from medicines to nano-electronics, can be explored using high energy photon beams. These beams must be controlled with ultra-precision using precisely curved optics and mirrors with perfectly smooth surfaces to probe molecular and atomic structures. To verify that these surfaces are free from nanoscale errors, the current measurement capabilities of the autocollimators used to confirm component quality must be improved.

The EMRP project **Angle metrology** developed a new centring device, ACenD, for precisely positioning small apertures on an autocollimator's optical axis enabling more surface irregularities to be identified in a sampled area. The project also investigated the use of a 'shearing method' - a mathematical analysis approach – that significantly improves error determination and compensation for the use of autocollimators.



© salkmesterke

MWO, part of Haag Streit, manufactures advanced optical testing instruments for assessing the complex components used in research beamlines, and is commercialising the project's ACenD device. One of the first users of this device was the Helmholtz Zentrum Berlin, who are currently acceptance testing the world's most precise mirror for the new European X-ray Free Electron Laser Facility (XFEL) in Hamburg.

Another early user of the ACenD device is the Diamond Light Source, the UK's national synchrotron light source. They have also introduced the project's 'shearing method' to assess the performance of autocollimators used for the acceptance testing of complex optic components. These improvements support optics manufacturers and improve the performance of a beamline, ultimately bringing researchers from different fields of science greater confidence in their measurements at beamlines.

## Perfect optics for fundamental researchers

Developing new materials for future industrial innovations or advances in drug development relies on discovering their nanoscale properties. Highly brilliant light beams produced by synchrotron or free electron laser facilities and manipulated by complex optical systems can provide this information. However, identifying system imperfections is challenging, as even a 1 nanometre flaw can create beam distortions. The autocollimators used to confirm near perfect optical components against specification require improved measurement accuracy to ensure that beam lines perform as expected.

With this objective, the EMRP project **Angle metrology** improved the performance of autocollimators – instruments for the contactless angle measurement of optical surfaces. This was achieved by creating novel image patterns which can be located on the autocollimator's detector with improved accuracy. The IP for this device has been patented and commercialisation is in hand to enable the reticle's use in developing the next-generation of autocollimators. Improving the quality of high intensity light beams will support European materials research which is fundamental to future innovations in many scientific fields.

## Precision robotic movements

Manufacturers of cars and planes rely on robotic machine tools to assemble parts with great precision. Translating computer generated voltages into 3D robotic movements requires a device to process signals - an angle encoder. As manufacturers produce and assemble increasingly complex parts, the €140 billion European robotics industry needs to control movements with ever increasing accuracy.

The EMRP project, **Angle metrology**, investigated the performance and the sources of measurement error for angle encoders. This included developing a self-calibration method that does not rely on external reference standards in a new optimised and cost-effective approach suitable for industrial applications introducing next-generation angle encoders based on multiple scanning encoder heads.

Fagor Automation, an automation technology manufacturer, - in collaboration with a non-profit technology centre IK4-Tekniker - used project knowledge to design a new angle encoder assessment machine fitted with a special multiple reading head angle encoder alongside software to reduce measurement errors. This allows greater precision in angle encoder calibration. As a result, Fagor's R&D department can now more accurately assess prototype encoder performance. Developing the measurement tools for increasing 3D movement precision is key to maintaining a competitive edge for the European robotics industry.



© mntbb

## Seeing the light

Europe is the world's second largest producer of photodiodes - light measurement devices - in a global market projected to be worth €766 million by 2026. To maintain this leading position, advances are needed to support growing demand for more precise light measurements in cutting-edge applications. Photodiodes are crucial to sensing applications in ICT, earth observation and healthcare, and are also used in realising the candela, the SI unit of luminous intensity against which other optical technologies are calibrated. As applications such as satellite and X-ray imaging require greater light sensitivity, new designs are needed to replace existing silicon photodiodes, which are reaching their physical limits.

The EMRP project **New primary standards and traceability for radiometry** developed a new 'black photodiode' which captures almost all incoming light, improving on existing designs where 20-40 % is reflected. ElFys Oy, a Finnish start up, is now commercialising the photodiode and has already won customers in security imaging. It anticipates significant interest in other areas, including satellite imaging, for which it has received European Space Agency support. The black photodiode's commercialisation will help Europe remain a leading global player in optical technologies.

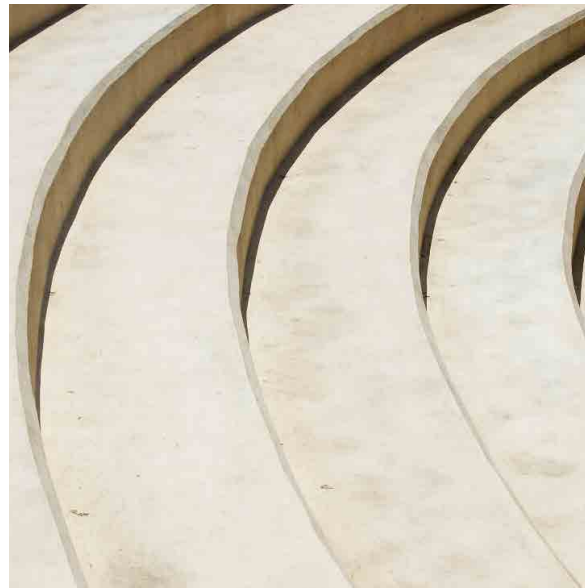


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## Improving sub-nanometre accuracy

Semiconductors, bio-materials and other nanoscale innovations rely on the precise production of minuscule features. Europe is the leading manufacturer of the advanced microscopes that are used to verify these features. As features get even smaller, new sub-nanoscale reference standards will be needed to demonstrate the accuracy of the next-generation of microscopes.

The EMRP project, **Crystalline surfaces, self-assembled structures, and nano-origami as length standards in (nano)metrology**, created prototype standards based on the fundamental properties of nature that create regular crystalline structures. By controlling environmental conditions during silicon crystal formation, they created highly regular 'staircase' like structures of less than 0.3 nm spacing - 20 times smaller and 10 times more accurate than existing standards. However, before these standards can be more widely adopted by industry, further validation is required by the international measurement community.



© spinout

Sensofar develops high-end optical measurement instruments, and was keen to explore the limits of its current microscopes using the staircase standard. This has enabled the company to demonstrate that its products exceed client expectations and will underpin their next-generation of ultra-high resolution measurement tools. Improvements in sub-nanoscale measurements will drive innovations at ever smaller scales in electronics and other nanoscale industries.

## Better industrial insulation materials

Insulation materials play a vital role in reducing heat loss in high temperature processes, such as steel production and oil refining. Energy use can represent up to 75 % of the cost of petrochemical production, therefore keeping heat in the system with insulating materials is vital to cost saving, energy efficiency and competitiveness.

Accreditation laboratories assess the thermal properties of insulating materials and certify them accordingly. However, up to 15 % measurement variation has been shown between accreditation laboratories.

The EMRP project **Metrology for thermal protection materials**, identified and characterised calcium silicate reference materials to allow better comparison between laboratories. It also developed a new testing regime using smaller samples in order to overcome a common problem of samples bowing when heated.



© Nostalgie

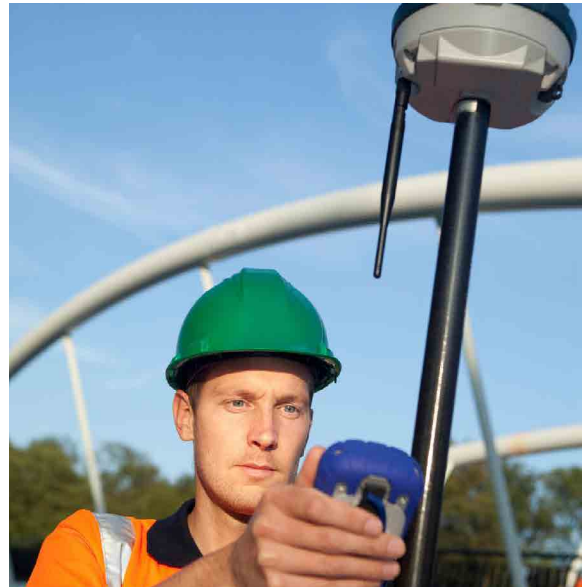
As a result of participating in the project, FIW, an accredited German calibration laboratory has been able to identify and remove sources of uncertainty from its accreditation process, thereby developing robust links to the SI. This gives its customers greater confidence in FIW's test certificates, which will help bring new products to market, and it will help manufacturers to make informed choices in order to reduce costly heat losses from high temperature processes.



## Greater accuracy for long distance surveying

The EU exports €107 million worth of electronic distance meters annually for surveying on construction sites. Confirming a meter's performance currently relies on it being taken to accurately known measurement 'base lines'. Easy-to-use, transportable calibration systems are needed to demonstrate that meters continue to achieve the 1 mm precision required over distances of several kilometres between calibrations and without the need to remove them from service.

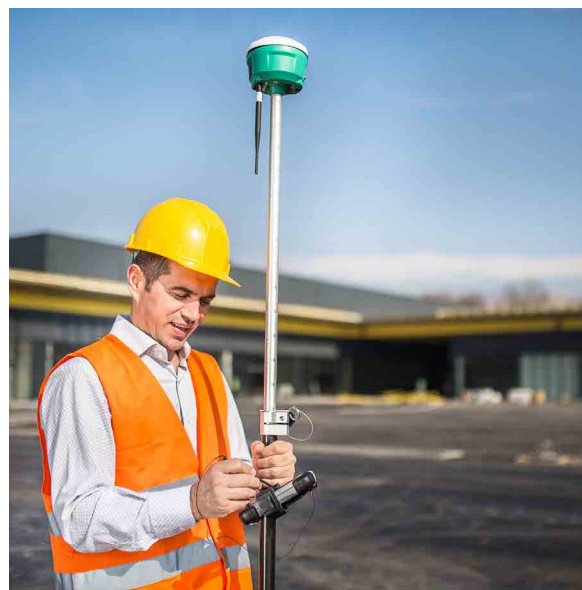
The EMRP project **Metrology for long distance surveying**, developed a transportable laser-based system from commercially available communication components, suitable for confirming the accuracy of instruments routinely used for surveying distances greater than several kilometres. It uses a technology that can make it resistant to the inaccuracies created by temperature variations along the length of the laser beams used. Called the 'TeleDiode', it is now being further developed prior to commercialisation to produce a novel, yet highly accurate, simple to use device for transferring the SI metre from installed instrumentation at 'base lines' to the more portable devices that are used by surveyors on construction sites.



## Greater accuracy for satellite based surveying

Long distance surveyors assessing sites for the construction of roads or large building complexes often rely on global navigation satellite systems (GNSS) for accurate measurements. Whilst simple to use and cost-effective, this approach cannot at present match the 1 mm precision over several kilometres of other terrestrially based surveying techniques. Understanding sources of GNSS-based measurement error and methods for their mitigation will enable GNSS to achieve the demanding accuracy required for large scale civil engineering.

The EMRP project **Metrology for long distance surveying**, investigated sources of measurement error in GNSS systems, such as the effect of inaccuracies in satellite and ground-based measurement antenna positioning. A better understanding of the sources of GNSS measurement errors developed in the project has enabled measurement uncertainties as low as 0.5 mm for 1-kilometre measurements to be achieved under favorable conditions.



To make this information accessible to the surveying community, a measurement good practice guide has been web-published in both English and German by the Society for Geodesy, Geo-information and Land Management (DVW) based on project investigations. DVW is keen to promote best measurement practice to their membership who need accurate measurements to support projects ranging from civil engineering to land stability.

## Demonstrating building material safety

Materials used in buildings and bridges need to withstand extremely large loads, whilst being subject to design and cost constraints. This relies on demonstrating that materials meet anticipated in-service loading within a required safety margin. Testing conducted at high loads confirms this, but improved accuracy with robust links to the SI units and methods for monitoring that loads have been reliably transferred to test samples are needed to underpin public safety.

The EMRP project **Force traceability within the meganewton range**, investigated how transducer performance is affected by varying environmental conditions, such as humidity and temperature, and generated statistical models to predict transducer behaviour. The project also investigated different transducer designs. This led to the discovery that the most accurate transducers are compact in both size and shape.



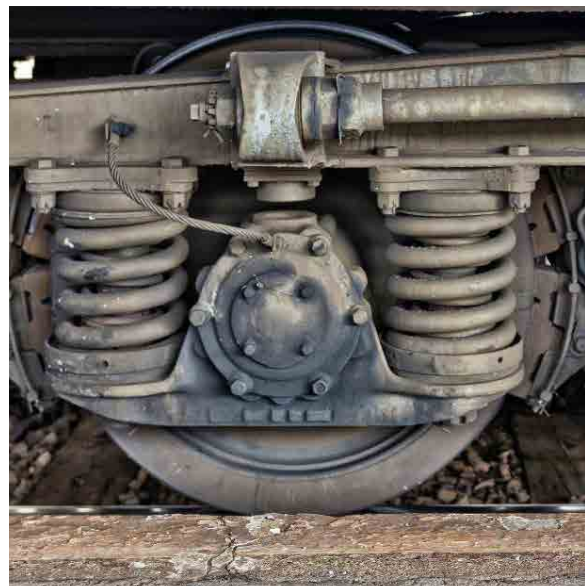
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GTM Testing and Metrology GmbH, a company that manufactures transducers, have used the project's outputs to improve their transducer designs, which gives their customers more accurate and reliable load measurement systems. Improving the accuracy of construction material testing, used to underpin building integrity and public safety, will enable industries to improve designs and reduce costs without compromising safety standards.

## Testing for safer suspension systems

Spring-loaded movement dampening systems are essential to prevent earthquake damage to tall buildings as well as smoothing rail travel at high speeds. To confirm these are fit for purpose and that they meet European safety standards, materials and components must be tested to ensure these can withstand high in-service loading. Improved testing methods are needed to provide the reliable measurements that underpin public safety.

The EMRP project **Force traceability in the meganewton range**, developed a novel high-load measurement system for transferring load accuracy from highly precise laboratory test machines to those in industrial settings. The system can record forces applied in three directions, based on six load measuring 'legs' and for the first time this provides information on machine alignment, which is a major source of testing error.



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EasyDur Italiana, manufacturers of high-load test machines for springs, are commercialising the hexapod. This will give EasyDur's customers a reliable method for confirming test machine alignment, and it will provide them with ongoing performance confirmation for machines applying high loads to springs to confirm their strength. This is vital for ensuring that railway components meet in-service requirements and conform to European safety standards.

## Accuracy for moisture measurements

Many industries – such as paper, pulp, wood products, food and pharmaceuticals - need to measure and manage the moisture content in their products. To improve the quality control of these products, better links to the SI units are needed for moisture measuring instruments.

The EMRP project, **Metrology for moisture in materials**, developed four highly accurate methods for determining moisture content. These were used to characterise different reference materials, which in turn were used to evaluate industrial 'Loss on Drying' techniques - the standard method for calibrating production line measurement instruments.

JMK Instruments Oy, a Finnish calibration laboratory, took part in a comparison exercise based on the project's outcomes: comparing its loss on drying method to the highly accurate project techniques. It identified improvements which bring greater accuracy and traceability to its measurements, and as a result it has received accreditation for performing moisture measurements on pulp, paper and board.

JMK Instruments Oy can now provide more accurate and reliable calibrations of paper measurement instruments, improving the production quality of paper, an industry which contributes 20 % to the Finnish economy.



## Improving biofuel moisture assessments

Replacing fossil fuels with biofuels, like wood chips, for district heating and electricity generation helps countries achieve carbon neutrality. The moisture content of wood chips varies with tree species and the season, leading to differences in weight and poorer combustion efficiency. Greater reliability for the time-consuming 'loss on drying' moisture assessment method is needed to help prevent disputes and payment delays between wood chip suppliers and consumers.

The EMRP project **Metrology for moisture in materials**, improved the accuracy of highly precise National Measurement Institute (NMI) moisture measurements, and used these to characterise new reference materials that are suitable for comparing the loss on drying techniques performed by different laboratories to reduce result inconsistencies.

HedeDenmark, suppliers of large quantities of wood chips to Danish district heating plants, is benefitting from the greater reliability of the loss on drying method developed in this project. Reducing measurement inconsistencies has improved result comparability between HedeDenmark and its customers. A follow-on project, funded by the Danish Energy Agency, is building on this project's outcomes to develop point of delivery technologies for assessing wood chip moisture content. Reducing payment delays and increasing measurement accuracy is key for promoting the growth of sustainable forestry to meet EU targets for carbon neutrality.





## Further information

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

<https://www.euramet.org/emrp-industry-si-excellence-2012>

Other projects in the EMRP SI Broader Scope theme can be found at:

<https://www.euramet.org/emrp-health-si-newtech-2011>

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 €400 million. The EMRP facilitates the formation of joint research projects between different NMIs and other organisations, including businesses, industry and universities.



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