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Review

Metrology in electricity and magnetism: EURAMET activities today and tomorrow

F Piquemal¹, B Jeckelmann², L Callegaro³, J Hällström⁴, T J B M Janssen⁵, J Melcher⁶, G Rietveld⁷, U Siegner⁶, P Wright⁵ and M Zeier²

¹ Laboratoire national de métrologie et d'essais (LNE), 78197 Trappes, France

² Federal Institute of Metrology (METAS), CH-3003 Bern-Wabern, Switzerland

³ Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce 91, I-10135 Torino, Italy

⁴ VTT Technical Research Centre of Finland Ltd (MIKES), Tekniikantie 1, 02150 Espoo, Finland

⁵ National Physical Laboratory (NPL), Hampton Road, Teddington, TW11 0LW, United Kingdom

⁶ Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

⁷ Van Swinden Laboratory (VSL), Thijsseweg 11, 2629 JA Delft, Netherlands

E-mail: francois.piquemal@lne.fr

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Abstract

Metrology dedicated to electricity and magnetism has changed considerably in recent years. It encompasses almost all modern scientific, industrial, and societal challenges, e.g. the revision of the International System of Units, the profound transformation of industry, changes in energy use and generation, health, and environment, as well as nanotechnologies (including graphene and 2D materials) and quantum engineering. Over the same period, driven by the globalization of worldwide trade, the Mutual Recognition Arrangement (referred to as the CIPM MRA) was set up. As a result, the regional metrology organizations (RMOs) of national metrology institutes have grown in significance. EURAMET is the European RMO and has been very prominent in developing a strategic research agenda (SRA) and has established a comprehensive research programme. This paper reviews the highlights of EURAMET in electrical metrology within the European Metrology Research Programme and its main contributions to the CIPM MRA. In 2012 EURAMET undertook an extensive roadmapping exercise for proposed activities for the next decade which will also be discussed in this paper. This work has resulted in a new SRA of the second largest European funding programme: European Metrology Programme for Innovation and Research.

Keywords: electricity and magnetism, EURAMET, fundamental and quantum metrology, low frequency, power and energy, radio frequency and microwave, SI units

(Some figures may appear in colour only in the online journal)

List of used acronyms

• Institutes and organisations

AGU Abdullah Gül University (Turkey)

APMP Asia Pacific Metrology Programme

BIPM International Bureau of Weights and Measures—
Bureau international des poids et mesures

CEN European Committee for Standardization—Comité
européen de normalisation



RF&MW	Radio frequency and microwave
RMO	Regional metrology organization
SC	Supplementary comparison
SDO	Standards development organization
SET	Single electron transport
SI	International System of Units—Système international d'unités
SPM	Scanning probe microscope
SQUID	Superconducting quantum interference device
SRA	Strategic research agenda
TC	Technical committee
VNA	Vector network analyser
VT	Voltage transformer

1. Introduction

Metrology is set to undergo a dramatic change in 2018 with the proposed revision of the International System of Units (SI) at the next 26th General Conference on Weights and Measures (CGPM) [1, 2]. At the same time, disruptive technologies such as the Internet of Things, quantum engineering and nanotechnology are driving the fourth industrial revolution (Industry 4.0) [3].

The field of electricity and magnetism (EM) is a significant advancement in the evolution of industrial needs and measurement science, which began in the second half of the 19th century with the early use of electricity for communication followed by the application of electrical energy for power and light supply which marked the second industrial revolution. It was then imperative for trade and commerce but also for science to connect in a consistent way the growing field of electrical measurements (with new electrical quantities) to mechanical units [4, 5]. This was done in 1948 with the internationally adopted definition of the ampere, the first unit whose definition is linked to a fixed value of a fundamental constant, the vacuum permeability μ_0 , giving rise to the MKSA system and paving the way to the creation of today's SI in 1960 [6].

Since the discovery of the transistor in 1947 by Bardeen, Shockley, and Brattain [7], there has been a huge expansion in electronics, information, and communication technologies (ICT). This is sometimes called the third industrial revolution because of the accelerated automation [3], underpinned by the strong development of electrical measurement instrumentation and electromagnetic sensors. The field of electrical metrology now involves a considerable number of electrical quantities, about 50, with some of them ranging over more than 20 decades of magnitude and covering a frequency spectrum from direct current (DC) to terahertz, i.e. to the near-optical regime.

Modern electrical metrology can be illustrated by the switchover from analogue to digital meters, the increasing use of sampling algorithms, data analysis tools, modelling and simulation software. Other highlights are the proven measurement techniques regarding low frequency (LF) coaxial bridges [8], or vector network analysers (VNA) [9], as well as the development of new standards and methods dedicated to arbitrary wave form synthesizers, sources or meters of signals containing high harmonics, strong distortion or noise,

measurement set-ups for power quality parameters, high speed instrumentation, electromagnetic compatibility (EMC) issues, or even for material characterization from the macro to nanoscale. More importantly the advent of quantum voltage and resistance standards in the 1990s marked a decisive turning point for electrical metrology and triggered the long journey towards a revised SI [10, 11]. This journey started from the theoretical predictions of Josephson in 1962 [12] giving rise to the remarkable superconducting devices such as the Josephson voltage standard (JVS) [13, 14] and the superconducting quantum interference device (SQUID) [15, 16]. This was followed in 1980 with the discovery of the quantum Hall effect (QHE) by von Klitzing in a Si-MOSFET transistor [17] and recently by the observation of an unconventional QHE in graphene by Geim and Novoselov [18]. These quantum standards signalled the end of the last material artefact in the SI, the international prototype of the kilogram (IPK), and of the quirky ampere definition.

In recent years, the progress made in electrical metrology (as in other fields) took place against the backdrop of intensified cooperation between the National Metrology Institutes (NMIs) within the regional metrology organizations (RMOs). Whilst achieving closer scientific cooperation, the NMIs extended their regional collaborative actions towards their primary mission of providing their industries with internationally recognized national measurement standards and proven traceability of their calibration and measurement capabilities (CMC) to the SI units. This resulted in the exchange of technical and advisory support, the supply of traceability sources, and the organization of comparisons. The RMOs obtained a key position both at the regional level and at the international level as a result of their collaboration and laid the groundwork for the MRA of the International Committee of Weights and Measures (CIPM MRA) which was adopted in 1999 [19]. This process signified a metrological milestone in the globalization of worldwide trade.

EURAMET is the RMO for Europe. Like the other RMOs, EURAMET is responsible for the CIPM MRA. However, along with the other RMOs, EURAMET was able to develop and implement two successive research programmes thanks to the co-funding of national resources and European Union (EU) contributions: The European Metrology Research Programme (EMRP) and the European Metrology Programme for Innovation and Research (EMPIR). These programmes enable European metrology institutes to work jointly to meet grand challenges such as the revision of the SI and its implementation, the societal, environmental, and industrial issues including for example the energy transition, the industry 4.0, nanomaterials and quantum technology.

This paper begins with a short description of EURAMET (section 2). Then, section 3 discusses its activities in EM from the beginning of 2000 till today. It highlights the main scientific activities, particularly those within the framework of the EMRP and points out the key actions carried out for CIPM MRA activities. In section 4, we review the outcomes of a roadmapping exercise that EURAMET undertook in 2012 which provide insights into the field of EM metrology until approximately 2025. These roadmaps were used to define

the strategic research agenda of the new EMPIR program. Conclusions and thoughts on the long-term outlook are given in section 5.

2. EURAMET

EURAMET is the European RMO with 37 NMIs as members so far and more than 70 designated institutes (DIs) as associates [20, 21]. It was officially established as a registered non-profit association under German law (EURAMET e.V.) on 11 January 2007, substituting the former European organization EUROMET [22]. The latter was a collaborative forum in measurement standards, created on 23 September 1987 on the basis of a memorandum of understanding (MoU) and with its origin from the Western European Metrology Club (WEMC) in 1973. Over a period of two decades, EUROMET has pursued its assigned objectives of promoting cooperation between the NMIs, optimizing the use of member resources and services, improving measurement services, and making them accessible to all members including the facilities designed under EUROMET projects.

Since 1999, like the other RMOs, EUROMET then EURAMET reached an essential position in the framework of the CIPM MRA [19], in particular through its contribution to the organization of regional comparisons of standards and the management of the CMCs, which are periodically submitted by the NMIs or DIs for publication in the key comparison database (KCDB) maintained at the Bureau international des poids et mesures (BIPM) [23].

The first unfunded EUROMET research projects in the field of EM field, and in projects funded by the EU in the successive 4th and 5th Framework Programmes, showed significant success and demonstrated the power of fruitful collaboration between NMIs (see for example in quantum electrical metrology with the first two funded projects SETamp and Provolt dedicated to single electron transport (SET) devices and programmable Josephson voltage arrays, respectively). The launch of the iMERA (Implementing Metrology in the European Research Area) project in 2005, supported by the EU within the 6th Framework Program, continued to strengthen the cooperation in research and consequently helped improve the European metrological infrastructure. The aim was to establish suitable structures and procedures in view of the EMRP and to fund projects to meet the outlined objectives.

To take on this double challenge of managing the CIPM MRA affairs with the highest efficiency and developing a competitive metrological research infrastructure in Europe, required the establishment of EURAMET e.V as a dedicated legal entity.

The self-declared mission of EURAMET can be summarized as follows [20]:

- Develop and disseminate an appropriate, integrated, and cost-effective measurement infrastructure for Europe taking into account the needs of end users in industry, business, and government;

- Ensure that the European measurement infrastructure is internationally competitive and recognized, and is based on robust and high-quality science and R&D.
- Support members in meeting their own national requirements through collaboration and a balanced European measurement infrastructure.

To fulfil this mission, EURAMET relies on ten technical committees (TCs) to cover the different domains of physics and chemistry, such as the TC-AUV (acoustics, ultrasound, and vibration), TC-EM, TC-F (Flow) etc complemented by two transversal committees for quality management and interdisciplinary metrological matters. The TC for EM (TC-EM) is itself composed of four technical subcommittees dedicated to: (i) DC quantities and quantum metrology including nanomagnetism and spintronics, (ii) all low frequency (LF) quantities except power and energy measured over the frequency range below 1 MHz, (iii) power and energy at audio frequencies, and (iv) quantities measured at frequencies from 1 MHz up to the near-optical region (THz). The EURAMET organization is headed by a board of directors and administratively supported by a secretariat. The EMPIR committee manages the research programmes, and a research council gives strategic advice to the association.

3. EM activities in EURAMET

3.1. Research and development

Most of the highlights of European research in electrical metrology during the last decade resulted from numerous joint research projects (JRP) funded by the EMRP. This programme was initiated by EURAMET in 2007, updated in 2008 [24], and will end in 2017. To our knowledge this is the first international research programme established in the field of metrology. It has been constructed along two research themes dedicated to ‘grand challenges’ and ‘applied and fundamental metrology.’

The first theme ‘grand challenges’ incorporates the metrology research of an inherently multidisciplinary nature responding to the key socioeconomic challenges in the sectors of health, energy, environment, and new technologies which include nanotechnology, identified by the EU as a key enabling technology, and security-related technology (THz sources and detectors, quantum cryptography).

The second research theme addresses the grand challenges of fundamental metrology, i.e. the revision of the SI, defining all the units in terms of fixed numerical values of seven defining constants; the focused single-discipline and applied metrology through advanced the realization of base and derived SI units, and finally applied metrology to support innovation, products, and services (calibration, standardization, regulations).

A general overview of the EMRP projects in EM and statistics are given in appendix A. They have partly contributed to the highlights, which are summed up below, in four sections: DC and fundamental metrology, LF metrology, metrology for power and energy (P&E) related quantities, and radio frequency and microwave (RF&MW) metrology.

3.1.1. Fundamental metrology. In fundamental electrical metrology, Europe has a long and successful history with several notable highlights. It would not be an overstatement to say a large part of the original work in this field originated in Europe. First, Brian Josephson at the University of Cambridge proposed the interaction of microwaves with a superconducting junction which led to the primary standard for voltage [13, 14]. A decade later, Klaus von Klitzing discovered the QHE at the High Field Magnet Laboratory in Grenoble which quickly became the primary standard for resistance [25, 26]. On the basis of these two quantum standards, Bryan Kibble at the National Physical Laboratory (NPL) in the UK proposed the electrical kilogram through a watt balance experiment [27]. Finally, the origin of SET devices can be traced back to the early research on frequency-locked turnstile devices at the Saclay group of Michel Devoret and the Delft group of Hans Mooij [28].

The proximity of European metrology laboratories to these developments in academia led to a quick take-up by the EURAMET members. Over the last three decades, many collaborative projects have been undertaken to advance and disseminate fundamental metrology amongst European NMIs. Activities in these projects focused on producing reliable quantum devices for metrology, investigating the limits of quantization, developing measurement instrumentation, and formulating guidelines for proper usage. As a result, almost every NMI in Europe has access to and can operate primary resistance and voltage standards at the highest level of precision.

Despite these successes, the work in fundamental metrology is far from finished. Endeavours are still required for fundamental consistency tests. This comprises universality tests to verify the consistency of the same quantum effect in different materials and the closure of the quantum metrology triangle (QMT) to check the consistency of the Josephson effect, QHE, and SET, which are based on the same constants, the Planck constant h and the elementary charge e (figure 1). It is noteworthy that the QMT experiments address the quantum foundations of the Kibble balance and the quantum realization of the ampere.

In Europe there is a very large concerted effort to advance SET and close the quantum metrological triangle (QMT) at the level of 1 part in 10^7 before the planned 2018 redefinition of the SI [11, 28]. Researchers from the National Institute for Standards and Technology (NIST) set the standard in 1999, with their metallic 7 junction pump device, and achieved an accuracy of around 1 part per million for the closure of the triangle [29]. Several years later the NPL and the Physikalisch-Technische Bundesanstalt (PTB) developed the concept of tunable barrier pumping in semiconductor devices which has increased the accuracy of single-electron current sources to a few parts per 10^7 and increased the electrical current level by two orders of magnitude to nanoamperes which is crucially important for real-life applications [30–33].

The achievement of such a result has been made possible thanks to the development of an ultrastable low-noise current amplifier (ULCA) [34, 35] operating at room temperature. The performance of this device is determined by a resistance ratio that can be directly determined with a cryogenic current

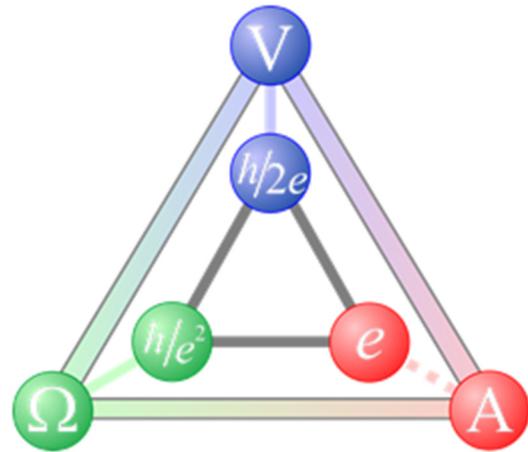


Figure 1. The quantum metrological triangle which shows the relationship between the three quantum electrical effects and the fundamental constants h , the Planck constant, and e , the elementary charge⁸.

comparator (CCC) device. This amplifier is already commercially available. Such a device and the tunable barrier electron pumps are very promising to realize the ampere in the framework of the revised SI, particularly for the current amplitude of 1 nA or less. For current intensity higher than 1 nA, another method for the quantum realisation of the ampere has been recently proposed by the Laboratoire national de métrologie et d'essais (LNE). This approach implements a quantum current standard by directly applying a Josephson voltage to a quantized Hall resistance and demonstrates a new record accuracy of $0.01 \mu\text{A A}^{-1}$ for a current range of 1 mA down to $1 \mu\text{A}$ [36].

In 2004, Geim and Novoselov at the University of Manchester first isolated a single layer of carbon atoms from pyrolytic graphite [18]. This extremely simple material, called graphene, possesses a plethora of amazing properties, one of which is an extremely strong QHE [37]. This discovery led to a surge of activity in the metrological community [38] for two important reasons. Firstly, the band structure of graphene is very different from semiconductor systems in which the QHE was originally discovered. This gives metrologists the opportunity to test the universality of the QHE which is important because theory is not able to prove that the von Klitzing constant R_K is exactly h/e^2 . The results of the universality test from NPL and LNE demonstrated agreement better than one part in 10^{10} [39, 40]. Secondly, because the QHE is so strong in graphene it provides an opportunity to realise it at elevated temperatures and much lower magnetic fields. This significantly reduces the infrastructure and complexity of the primary resistance standard and implies that many more laboratories around the world will be able to benefit from it. Recently, the NPL demonstrated the first prototype table-top cryogen-free quantum Hall system with an accuracy of a few parts per 10^9 [41].

⁸ It is sometimes referred to as a test of Ohm's law for quantum standards but one should remember that this is not strictly correct because the proportionality of current and voltage in the QHE has no relation to Ohm's law but instead is a consequence of electron motion resulting from the Lorentz force in magnetic field, although the mathematical form is the same.

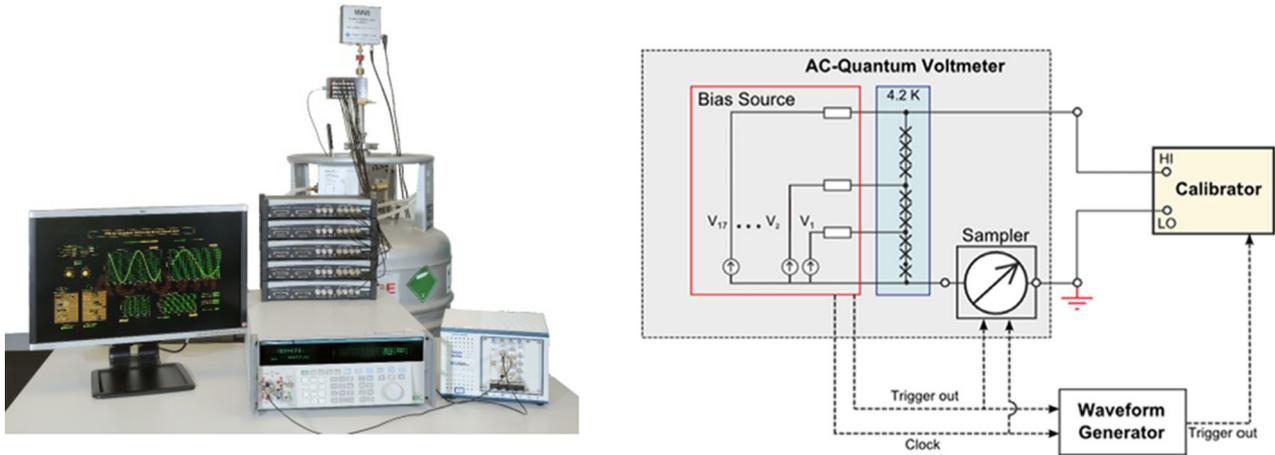


Figure 2. AC quantum voltmeter used to calibrate a calibrator, after reference [45].

Josephson arrays for DC voltage calibrations are more or less perfect and no further improvements are required. Instead the community is focusing on developing standards for AC electrical metrology with primary quantum traceability [42]. There are two types of technologies for realizing this, pulse driven arrays and binary segmented arrays. In Europe, PTB has developed complete and versatile fabrication lines for both types of technology [43, 44]. The technology is complex and expensive and research has greatly benefitted from a number of collaborative European projects in this field. As a result, in the not too distant future, commercial AC voltage calibrations with primary quantum traceability will become available [45].

The electrical kilogram is an extremely difficult experiment which will take many years (decades) to complete. It is a cross disciplinary experiment drawing on technology from various fields of metrology (electrical, mass, dimensional, gravimetry, time and frequency, and materials). Consequently, only a few laboratories in Europe are involved in this activity. For about 16 years the Federal Institute of Metrology (METAS) and LNE have embarked on the development of Kibble balances and have already published the first Planck constant values in agreement with the existing ones at an uncertainty level of 3 parts per 10^7 [46, 47].

Science and technology continuously advances and metrology laboratories need to develop their capabilities in tandem with this to be able to support such new applications. In recent years applications based on fundamental quantum mechanical effects such as superposition and entanglement have gained much interest. These applications range from quantum communications and quantum computing to quantum enabled sensing and metrology (see section 4 and appendix B) [48, 49]. At the moment there is no metrology to support these applications. NMIs with experience in quantum electrical standards are very well placed to work on this type of technology because of their experience in low temperature physics and ultra-sensitive measurement technology. Recently, the first collaborative projects have started in EMPIR to develop new capabilities in quantum technology and to address the need for metrology in this new area.

3.1.2. LF metrology. Due to several successful EMRP projects, mainly carried out by scientists from the field of fundamental metrology, practical quantum standards have been developed which now can be used not just in the everyday routine work of NMIs but are also commercially available and starting to enter industrial calibration labs. The development of standards for DC is followed by a similar process for AC standards. Great progress on AC quantum voltage standards has been made (figure 2). The main obstacles for the application of quantum Hall devices in LF impedance metrology have been overcome to the end that these devices are able to achieve uncertainties which are lower or at least comparable to those provided by classical techniques [50, 51]. This development was already foreseen in 2012 with the setting up of the TC-EM roadmaps in the preparation phase of EMPIR (see section 4).

The presence of mixed-signal electronics in LF metrology setups is increasing. The precision of digital-to-analogue and analogue-to-digital converters in the audio frequency range is nowadays below the part per million level; periodic or on-line calibration [52] with Josephson sources allow the design of new instruments for primary metrology.

Consider for example digital impedance bridges [53], where several sinewave signals flowing in the bridge mesh are generated by digital synthesis and/or measured by synchronous sampling. The digital bridge allows fast and automated measurements with a relatively simple architecture. In digitally assisted bridges the accuracy is still guaranteed by an electromagnetic ratio standard (an inductive voltage divider, or a current comparator) and thus the performances and the limitations (fixed set of ratios and frequencies available) are similar to traditional transformer bridges. Fully digital bridges are voltage ratio bridges where the ratio accuracy is directly given by the properties of the converters employed: they allow for the measurement of arbitrary impedance ratios; the corresponding accuracy is presently limited to parts per 10^5 , but is expected to improve in the future. A special case of a fully digital bridge is a Josephson bridge, where two Josephson sources (either binary [54] or pulse driven [55]) constitute the bridge ratio standard.

Digital methods also allow for the accurate synthesis of arbitrary impedances [56]. High-frequency impedance metrology [57], in the range 100 kHz to 100 MHz, is presently performed with traditional bridges and methods; however, the working frequency of precision analog-to-digital converters (ADC) and digital-to-analog converters (DAC) is continuously increasing and it can be expected that digital methods will also be applied in this field.

3.1.3. Metrology for power and energy. The EU renewable energy targets have been a significant driver for metrology in the AC power and energy field. Electricity network operators are faced with significant challenges to integrate high penetrations of intermittent renewable generation whilst maintaining the supply quality and reliability. The term ‘smart grid’ is often used to describe the new technologies and methodologies that are emerging to manage these future energy systems.

NMIs have had close relationships with the electricity utilities over the previous decades and much of the progress in AC power measurements with lab-quality sinewaves at 50 Hz have been driven by the need to support traceability in revenue settlement. As a result, the accuracies of commercial instruments are of an order of $10 \mu\text{W W}^{-1}$ and the uncertainties available at some NMIs [58] in AC power measurement are commensurate with providing traceability for this industrial need.

As the smart grid revolution has gathered pace, the emphasis on AC power metrology is directed toward applied field measurements in support of technologies and utilities. Much of the EMRP/EMPIR funding over the past decade has supported this emergence of field-based activity, which must face multiple new challenges such as harsh environments, complex signals with amplitude and phase modulated distortion and noise.

NMIs such as the Technical Research Institute (SP) of Sweden and the National Research Council (NRC) in Canada have pioneered on-site power metrology, responding to the request of their national utilities to provide on-site calibrations of high voltage instrument transformers and the associated metering. Building on this, EMRP projects have both developed and applied on-site metrology infrastructure to support the development, planning, and operation of power grids [59].

Instrument transducers are used to transform the high voltages and currents in an electricity system to measurable amplitudes. During on-site calibration the reference transducers must often be connected without the need to dismantle parts of the grid and ideally be connected without interrupting the power. Rogowski coils and openable core current transformers (CTs) have gained popularity as these are of split design and can be wrapped around existing conductors to measure current. New split cores designs have been introduced by the Van Swinden Laboratory (VSL) and the Czech Metrology Institute (CMI) [60].

The calibration of voltage transformers (VT) for medium voltage grid is often performed on-site, by comparison with inductive standard voltage transformers. Istituto Nazionale di Ricerca Metrologica (INRIM) has designed a medium voltage portable cast resin insulated resistive-capacitive divider for on-site calibration. Exploiting its more compact, light, and

portable design it can be used as an alternative to standard VTs, with on-site uncertainties in the order of 5 parts per 10^4 and $300 \mu\text{rad}$ [61].

For medium and high voltage power quality measurements the existing instrument transformers are the only possibility because the supply cannot be interrupted and it is unsafe to make a live installation. Even though the ratio and phase displacement errors of these instruments remain unknown, they can still be useful for relative harmonic measurements. Their frequency response can be estimated based on knowledge about their internal construction, or by calibrating a transformer of identical design in the laboratory. PTB has developed laboratory facilities for frequency response measurement of CT [62] and INRIM has developed a wideband divider for power quality measurements on medium voltage networks [63]. Works carried out by the Institute of Metrology of Bosnia and Herzegovina (IMBH) and VSL indicate the possibility of using phasor measurement units (PMU) (see below) to transfer the ratio calibration of one reference VT to another remotely located VTs on the same network.

Having transformed and digitized the three phase signal, the measurement becomes an algorithm and digital signal processing exercise. As the signals contain harmonics and are non-stationary in amplitude and phase (frequency of the mains supply is not a constant 50 Hz), the measurement of signal parameters involves sample windowing which leads to trade-offs in frequency and time resolution in the measurement.

Complex power quality parameters such as harmonics, interharmonics, and flicker have become important metrics for network operators. These parameters require complex algorithms over and above the Fourier Transform that is only suitable for stationary signals. NPL pioneered lab-based power quality (PQ) measurement for EMC compliance calibrations in the 1990s including several algorithms for the accurate measurement of fluctuating harmonics and flicker. Again, taking this metrology into the field is non-trivial; INRIM, PTB, NPL, and the Slovenia Institute of Quality and metrology (SIQ) have all developed so-called asynchronous sampling algorithms that allow measurements to be made in the presence of changing mains frequency [64]. The propagation of measurement uncertainty through these multiple input complex algorithms is in itself a significant challenge and Monte Carlo simulation is the preferred tool to estimate uncertainties in accordance with the GUM [65].

Wide-area measurements using PMUs have an emerging presence in electricity networks. These instruments are used as a group, which is time synchronised by GPS. This enables the signal phases across wide areas to be measured. PMUs have many applications on power networks, including for example measurements of oscillating power flow, changes in power frequency, and power system impedance. GPS-synchronised measurements are also being used to determine PQ propagation characteristics to manage the operation of smart grids. METAS, INRIM, LNE, and VSL have worked closely to develop calibration infrastructure for PMUs in the last few years. Work on dynamic signal measurement (non-stationary) has involved improved algorithms and associated calibration infrastructure [66].

New techniques have also been developed for high voltage testing. SP has developed a 1000kV DC voltage divider, which is made up of separate 25 kV sections that are individually calibrated and then stacked together as their laboratory reference. For on-site calibrations a modular 1000kV direct voltage divider was designed, manufactured, and calibrated as a joint effort of VTT Technical Research Centre of Finland (MIKES), SP, VSL, PTB, and the TÜBİTAK Ulusal Metroloji Enstitüsü (UME) (figure 3). The combined uncertainty for 1000 kV DC measurements is $16 \mu\text{V V}^{-1}$ ($k = 2$) [67].

The future of AC power metrology is driven by the needs of smart grids and the requirement to measure the efficiency of grid components and devices developed for renewable energy or energy saving. This also includes the support of novel sensor technologies that are being increasingly widely applied in power networks (e.g. optical sensors based on the Faraday effect, hybrid electrical/optical sensors, systems for voltage measurement using the Pockels effect, or upgraded conventional instrument transformers with digital or optical readouts) [68]. This future implies a continuing shift away from precision lab-based metrology towards fit-for-purpose practical measurements within the metrological framework of traceability and uncertainty.

3.1.4. RF&MW metrology. The requirements in RF&MW metrology are largely driven by technological advances, most notably the increasing data rates in communication technology and the growing complexity of integrated and automated systems. The impact of the technological progress is wide and affects both society and the economy. Electromagnetic signals need to be generated, transmitted, and detected reliably and fast, whilst omitting and controlling unwanted effects related to the exposure to and interference with electromagnetic radiation. This pretty much defines the scope of R&D projects related to RF&MW metrology.

Parts of RF&MW metrology are strongly rooted in the engineering sciences with a distinguished flair for clever and very practical solutions for measurement problems. The more recent research in RF&MW has led to an extension towards modern scientific methods, acknowledging advances in computer technology and progress in underpinning fields, as for example related to measurement uncertainties. It can be observed that numerical EM field simulations start to play an increasingly important role in the characterization of measurement standards and in the understanding of effects influencing the accuracy of the measurements. Advanced methods to evaluate measurement uncertainties through refined modelling and with the support of adequate software have been introduced.

Scattering parameters (S-parameters) are fundamental RF&MW measurement quantities playing a distinct role in the design of electromagnetic circuits that are operated at high frequencies. SI traceable measurements of S-parameters have a long history with established but somewhat antiquated procedures that are not easily applied at higher frequencies as for example demonstrated by VSL [69]. METAS has introduced new and improved traceability schemes which lead to more consistent and reliable results [70, 71]. In addition, the NPL, CMI, Czech Technical University Prague (CTU), University of



Figure 3. The modular 1000kV divider in a high voltage laboratory. Left, HVDC source and its divider; right, multicolour modular divider.

Leuven (KU Leuven), University of Leeds (ULE) and Keysight Technologies (Keysight) have extended metrology support beyond the standard 50Ω impedance in coaxial lines to cover extreme impedances [72], nonlinear measurements [73], higher frequencies [74], and other transmission line types [75, 76]. Electronic calibration units promise to replace mechanical measurement standards but are limited in accuracy due to temperature effects, as investigations by PTB and METAS have shown [77].

The field of EMC covers the testing of emission and immunity requirements of equipment with respect to electromagnetic radiation. It is an area strongly dominated by normative regulations but nonetheless relies on reliably calibrated test equipment. Using digital signal processing a new time-domain method for conducted emission testing with an oscilloscope has been successfully developed and tested by UME and Universitat Politècnica de Catalunya (UPC) [78]. This constitutes major progress for the EMC analysis of transient disturbances. LNE and SIQ have made available new coaxial-type to banana adaptors for precise calibrations of line impedance stabilization network (LISN) [79]. Full traceability is established with the characterization of these adaptors through EM field simulations. Different EMC testing methods for alternative test sites have been investigated systematically by UME [80, 81]. This provides a unique reference for all testing laboratories applying a non-conventional testing method, e.g. for onsite testing. At METAS major progress on the validation of conducted immunity test methods has been achieved through the development of a reference source [82].

Material characterization is crucial for product development because simulation of new devices requires precise knowledge of material properties such as permittivity, permeability, and conductivity. Calibrated measurements of permittivity and loss tangent on the nanoscale, i.e. down to 100 nm resolution, have been demonstrated by METAS, Johannes Kepler University Linz (JKU), Eidgenössische Technische Hochschule Zürich (ETHZ), and Keysight for frequencies up to 20 GHz [83, 84]. Such measurement systems combine techniques from dimensional and electrical metrology. The measurements are useful for detecting faults in the fabrication of semiconductors and to enable new nanotechnologies. At PTB

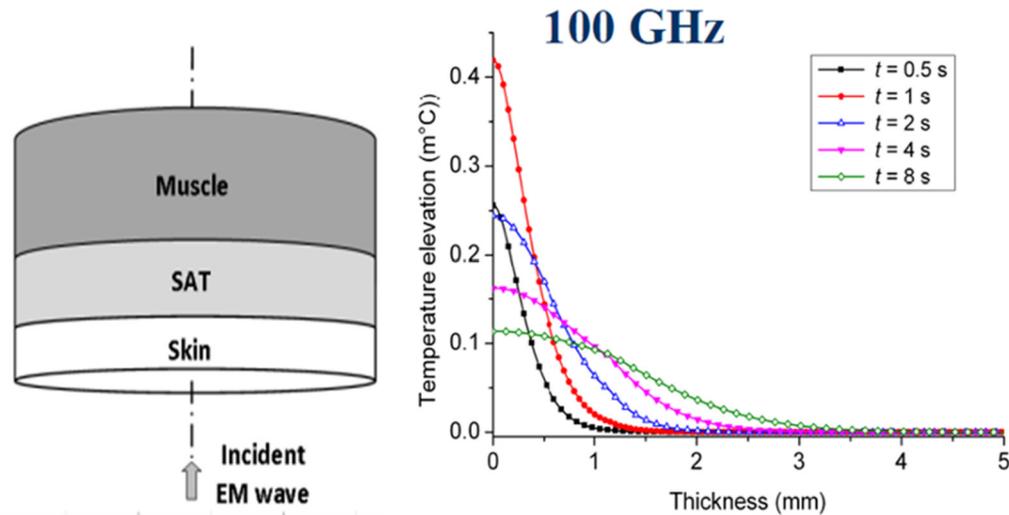


Figure 4. The left side illustrates a multi-layer skin model, which was used to investigate the heating effects of THz radiation (as part of the ‘THz Security’ project). The results on the right are based on numerical simulations performed with a graphics-processing-unit (GPU)-based boundary element code for electromagnetic and thermal numerical analysis using coupling electromagnetic wave propagation and a bioheat thermal equation. Courtesy of Oriano Bottauscio (INRIM).

and NIST, thin films and bulk substrates are characterized with split cylinder cavity and coplanar waveguide techniques up to 80 GHz [85, 86]. The investigated thin films are functional thin films and ferroelectric thin films. The conductivity of copper traces on printed circuit boards is measured at the Polish National Metrology Institute (MG) and the Warsaw University of Technology (WUT) with a dielectric resonator [87]. This is important for cost saving in manufacturing as simple FR4 substrates are used for increasingly high frequencies. Additionally, ceramics with ultra-high relative permittivity (up to 3000) have been measured in coaxial cells.

Remote sensing techniques using THz frequencies, traditionally being used in scientific applications like radio astronomy, have been commercialized for security applications over the last years. Measurement traceability for sources and detectors is needed to comply with safety limits and future regulations. PTB has successfully performed traceable measurements of power levels up to 5 THz [88]. New means for dissemination, including new detectors [89] and a new portable, commercially available room-temperature radiometer have been developed in cooperation with Sensor und Lasertechnik Neuenhagen (SLT). The traceability of relevant spectrometer parameters has been established and the accuracy of different types of spectrometers has been compared [90] by the PTB, LNE, and University Tun Hussein Onn Malaysia (UTHM). Realistic dosimetry has been investigated with the development of numerical skin models and phantoms as a basis both for the performance and safety evaluation of THz scanning systems [91]. An example is shown in figure 4.

Design and production of electronic high-speed systems often require the exact measurements of continuous wave and pulsed high-frequency signals in the time domain. The PTB development of a laser-based vector network analyzer [92] and new asynchronous sampling techniques with femtosecond lasers [93], developed in cooperation with National Instruments Belgium (NIB), constitute major advances in this

field. Using high-speed instrumentation for measurements over long time windows often yields time traces with more than 10^4 data points. In a collaborative effort among the NPL, VSL, MIKES, and Instituto Nacional de Technica Aeroespacial (INTA) it was demonstrated how correlation effects in the uncertainty evaluation of such large data sets can be managed with appropriate algorithms and software support [94].

Newly evolving digital communication systems require the reliable generation, transmission, and detection of digital signals. The efforts of the UME, INRIM, METAS, NPL, CMI, Abdullah Gül University (AGU), Delft University of Technology (TU Delft), Institut d’électronique et de télécommunications de Rennes (IETR) and Orbit/FR-Europe GmbH (Orbit) have result in providing metrological support through the characterization of mm-wave antenna arrays operating at the required frequencies [95–97] and the traceable calibration of instrumentation, which is used to detect and generate digital signals [98, 99]. More specifically measurement methods for signals emitted from long term evolution (LTE) base stations have been made available by METAS and ETHZ [100] to reliably determine the power levels of the latest telecommunication standard, which is currently being adopted globally.

3.2. CIPM MRA activities

The research and development activities performed within EURAMET EMRP projects have a direct impact on the type, range, and quality of the calibration services provided by the NMIs. The existing and new services are framed, since its signature in 1999, in the Mutual Recognition Arrangement of National Measurement Standards and of Calibration and Measurement Certificates issued by National Metrology Institutes (CIPM MRA) [19]. This declaration drawn up by the CIPM was originally signed by 40 directors of NMIs and international organizations, and includes 101 NMIs and 4

international organizations as signatories at the present time (2016); it also includes 153 DIs.

The objectives of the CIPM MRA are to establish the degree of equivalence of national measurement standards maintained by NMIs, to provide for mutual recognition of calibration and measurement certificates issued by NMIs, and to serve as the foundation for wider agreements in trade, commerce, and regulatory affairs. The technical basis of the CIPM MRA, that establishes the mutual confidence in measurements, is the set of results of key and supplementary measurement comparisons carried out by BIPM and the RMOs. The CIPM MRA lists the quantities for which calibration and measurement certificates are recognized by institutes participating in the agreement (see appendix C). A list of CMCs is maintained for each participating institute. The list is arranged in a database [23].

3.2.1. CMC. EURAMET TC-EM maintains a substantial part of the entire CMC set. At the last count (Aug 2016), there were 2095 entries backed by 763 matrices for 28 European countries. The set is organized into 12 service categories, which are specified in the ‘classification of services in electricity and magnetism’ [101] of the BIPM database. The service categories are further divided in sub- and sub-sub-categories (nearly 200 of them). To provide a comparison, the whole CMC set from all regional organizations in all fields amounts to more than 24 000 entries.

Since the signing of the MRA, the number of CMC entries continued to rise. This continuous growth is due to a number of factors: the success of the CIPM MRA within the metrology user community, and therefore the demand for more calibration services framed within the CIPM MRA; the continuous improvement in the technical capabilities of the European NMIs and therefore of the number of calibration services technically available from each NMI; the increase in the number of NMI and DI signatories of the CIPM MRA. Such an increasing number of CMCs in EM has created difficulties in the possibility of the general user being able to search, access, and compare the CMC entries.

A partial solution was implemented by EURAMET TC-EM in 2013, when it undertook an effort to rationalize the structure of all CMC entries, and reduce the overall number using matrices giving the uncertainty as a function of one or two parameters so that the number of entries is kept to the minimum possible while respecting the chosen classification scheme [101]).

Following EURAMET’s initiative at the level of the signatories of the CIPM MRA with the aim at reforming the arrangement to make it sustainable [102], a set of nine recommendations has been recently adopted by the CIPM [103]. They are focused on CMCs (better visibility, constrained proliferations, and improved efficiency of the review process etc) but also on governance and comparison issues.

3.2.2. Comparison. EURAMET TC-EM has launched a number of key comparisons (KCs), supplementary comparisons (SC), and comparisons projects throughout the years. At a given time, about 9 comparisons are running concurrently; 2–3 comparisons are completed each year. Figure 5 shows the

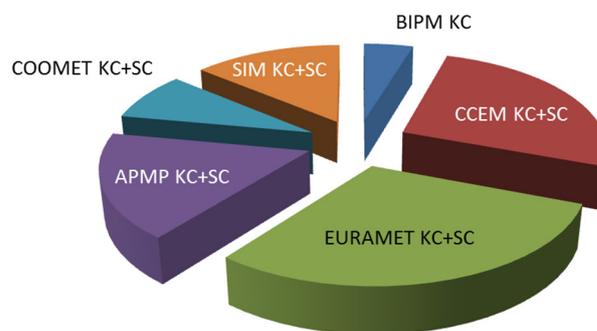


Figure 5. Pie chart of the 154 completed and 56 ongoing comparisons conducted by the regional organizations and the BIPM up to 2015.

total number of EURAMET EM comparisons to date, compared with those of the other regional organizations⁹.

The scientific, technical, and economic burden of piloting a comparison is considerable, and the duration of the commitment lasts several years. In an effort to reduce such a burden, EURAMET has taken several actions:

- Within the EURAMET TC-EM it is now common to share the pilot duties with two or more NMIs.
- In 2012 EURAMET TC-EM created a dedicated Comparison Task Force, which is developing an online comparison Toolbox helpful for both the pilot laboratory and the associated support group in the complete process of the comparison they are involved, with a special focus on being helpful for the less experienced NMIs and DIs. The Toolbox is based on a web interface that allows the Pilot, the Support Group and each participant to manage the travelling standards, to enter and process the comparison data, and to access the document templates, tutorials, examples, and data analysis software needed. The Toolbox is presently in its testing phase and has been adopted by EURAMET to also be employed within its other TCs.

3.2.3. Traceability landscape. Each CMC entry includes a declaration of the traceability source(s) for the particular calibration service. NMIs that do not hold primary standards or primary measurement capabilities are required to have traceability to the SI through the BIPM or through the calibration services of another NMI/DI recognized by the CIPM MRA [104].

Figure 6 shows an airline map of the traceability within European countries having declared CMCs in the EM area, providing evidence of a fully developed traceability network. A more detailed analysis of the evolution of traceability sources declared in the CMC entries, versus time, shows that since the adoption of the CIPM MRA:

⁹ Measurement comparisons are the basis of the CIPM MRA, but they were performed long before in the Electricity and Magnetism community. Some of these, predating or running during the signature of CIPM MRA were accepted as part of it.

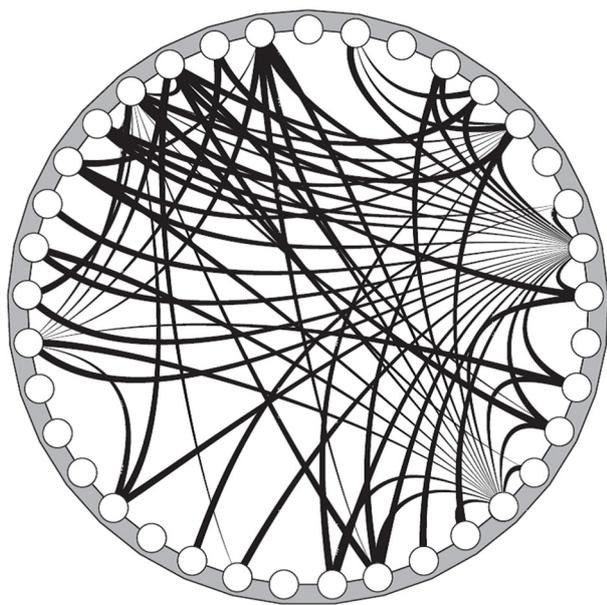


Figure 6. Airline traceability map among the 37 European countries for quantities pertaining to electricity and magnetism in 2015. The curved lines illustrate the traceability routes, the thicker end near the country which receives traceability from the country near the thin end, for some EM quantity. Only nine countries have no CMC in EM and none is ‘isolated’ (that is, they do not receive or provide traceability). Courtesy of Robert Wynands and Volker Wittstock (PTB).

- EURAMET NMIs offering traceability services to other NMIs has strongly increased.
- EURAMET NMIs are reducing their need for traceability from non-EURAMET NMIs.
- In general, EURAMET NMIs are developing autonomous capabilities in the primary realization of quantities related to low-frequency and power and energy fields, of major interest for manufacturing and energy-related industry calibration needs. For some quantities, such as DC voltage and RF quantities, an opposite trend is observed, and NMIs receiving traceability are increasing.

4. EM in the strategic research agenda of the EMPIR initiative

EMPIR is the second research programme implemented by EURAMET and based on co-funding by the EU through the Horizon 2020 framework programme and by 28 states. The plan covers the period 2014 to 2024, with the first call for projects launched in 2014 with final calls being scheduled in 2020.

Following on from the experience gained with iMERA+ and EMRP, and taking into account the expectations of the EU along its Europe 2020 Strategy, the EMPIR instruments address not only the basic research related to the SI (fundamental scientific metrology) and the research applied to industry and grand challenges, health, environment, and energy, but they address in more concrete terms the

issues relative to innovation and standardization while pursuing the long path of European capacity building (figure 7) [105, 106].

Indeed, as an extension of research programmes targeted for industry, EMPIR aims to contribute much more in the innovation chain through specific support activities for technology and knowledge transfer from metrology institutes to industrial companies and private market uptake. The transfer to a European and international Standards Development Organization (SDO) is an important integral part of EMPIR as well. This is arranged through annual calls for prenormative research projects, i.e. projects on research and development focused on metrology needed for European and international documentary standards. Last but not the least, the EMPIR work programme includes metrology capacity building which refers both to the development of high-level measurement capabilities (development of national standards, instrumentation, and methods to establish the traceability to the SI) and to non-R&D accompanying measures, the latter with the aim of developing the capabilities of EURAMET member states with weaker metrology systems.

The scientific and technical content of the EMPIR programme has been mainly drawn up from the inputs collected by the TCs during roadmapping exercises in 2012. Some insights gained in the EM field along the four strategic axes, fundamental scientific metrology, grand challenges, innovation, and prenormative, are described below. These are based on references cited in the text. References on a more general level can be found in [107–114].

4.1. Fundamental scientific metrology

The perspectives in fundamental metrology are envisaged in two directions: efforts to pursue quantum electrical metrology for implementing the revised SI, for continuously improving the various *mise en pratique* of the electrical units, metrological developments to undertake on the single atom and single molecule level, as support for sciences, and technologies related to atomic-scale devices.

4.1.1. Quantum electrical metrology. Today’s nanotechnology gives access to dimensions in which quantum effects govern the functionality of devices. This development creates opportunities to harness quantum effects for technology and to realize novel paradigms for functionality. Topical examples are quantum computing, quantum communications, quantum sensing, quantum simulation, and quantum metrology. Concomitantly, new quantum phenomena are being discovered at an ever increasing rate, which broadens the basis of quantum technologies. Since innovation relies on reliable and accurate measurements, new quantum-based metrology is required to advance quantum technologies and to exploit the results of fundamental science. Metrology itself should be based on universal standards that are independent of time and space. To this end, the SI base units are to be linked to fundamental constants of nature (figure 8). The links are realized by quantum effects, which provide unprecedented accuracy. In order to further increase the sensitivity and accuracy

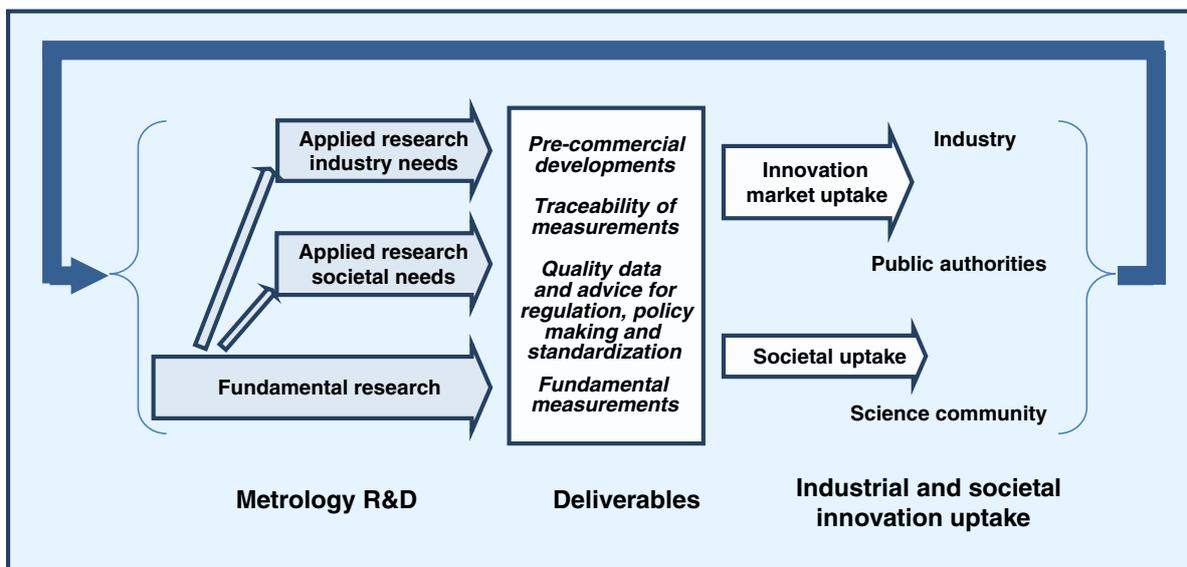


Figure 7. The metrology innovation chain, after reference [106].

of measurements, fundamental science will provide strategies to overcome noise limits and to reduce the invasiveness of measurements.

The activity plan in quantum electrical metrology is composed of four targets [115–118]: (i) practical realization of the new definitions of the SI units according to CIPM recommendations, (ii) fundamental consistency tests in electrical quantum metrology and determination of fundamental constants, (iii) simplified ‘fit-for-purpose’ calibration tools and intrinsically referenced calibration systems tailored to customer needs, and (iv) metrology for solid-state quantum engineering and quantum enhanced electrical SI standards. These targets are detailed in appendix B.

4.1.2. *Fundamental electrical metrology on the single atom/single molecule level.* Driven by very advanced ICT and applications for energy, health, and the environment, the ultimate down scaling of nanoelectronic and nanomagnetics devices will eventually lead to devices and materials having single-atom or single-molecule based functional units. Such ultimate scaling requires the control of the surface and device environment and eventually device assembly on the atomic scale. The testing of such ultimately scaled functional units in turn requires the measurement of advanced EM properties on the atomic level and thus with highest possible sensitivity. Ultimately routine measurements of single quantum entities of spin, flux, and charge in materials and devices are required.

The expected activities cover the development of characterization tools for nano and quantum structures and the implementation of traceable characterization of atomic-scale devices. At first, this implies accurate technical means for the detection and manipulation of single quantum entities (spin, flux, charge, photon) and new metrological concepts beyond classical EM measurements. Future metrology tools for nano and quantum structures will also have to take into account the interface of the quantum structures under investigation with their classical environment. This could for example include the back action of

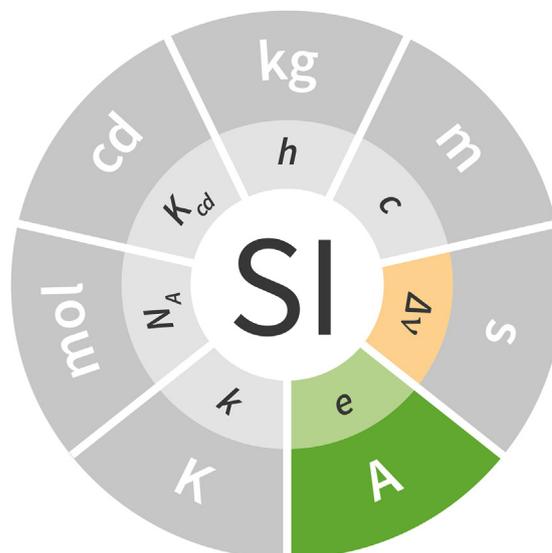


Figure 8. Revised SI logo for the ampere. In the revised SI, the seven base units (outer circle) can be realized from the seven defining constants (inner circle): the elementary charge, the hyperfine transition frequency of caesium, the speed of light in vacuum, the Planck constant, the luminous efficacy, the Avogadro constant, and the Boltzmann constant. Two defining constants (e and $\Delta\nu$) are necessary to realize the ampere.

the measurement on the measured quantum entity and a possible entanglement of the measured entity and the measurement probe. The question of the traceability of such highly sensitive measurements will have to be tackled. Here the usual path via reference materials can only be followed once robust atomic-scale assembled reference materials are available.

4.2. Grand challenges

Among the three grand challenges, undoubtedly energy is the most relevant for the electrical metrology community by the very nature of the topic and considering the experience of

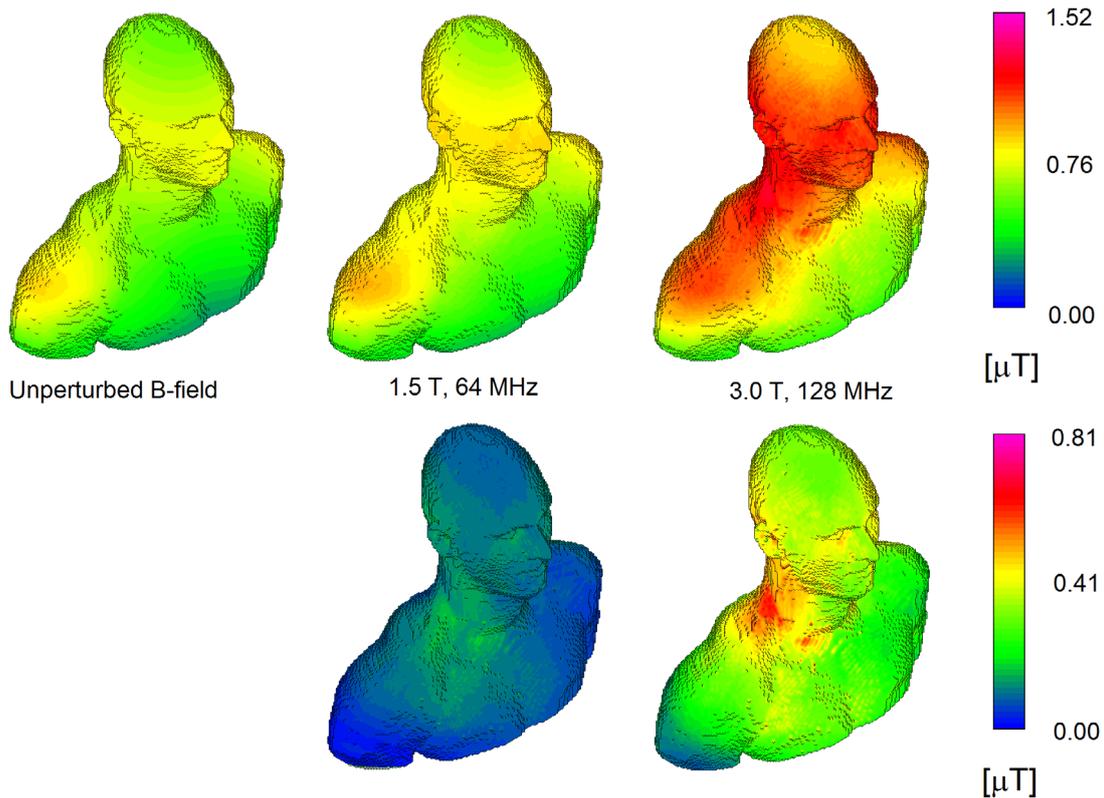


Figure 9. Head exposure to an MRI RF field with local distribution of B -field over the head surface. Top, from left to right, the unperturbed field and the field at 64 MHz and 128 MHz. Bottom, the variation ΔB with respect to the unperturbed case, after reference [119]. Courtesy of Oriano Bottauscio (INRIM) and Bernd Ittermann (PTB).

the past calls within EMRP. This remains true for EMPIR but some key outcomes are also expected in health and environment as shown below.

4.2.1. Health. The developments of new technologies for health care and monitoring, and increasing demands for precautionary measures on human exposure to environmental electromagnetic field (EMF) require underpinning electrical metrology, particularly in the RF to THz frequency range. The scope of electrical metrology activities focused on health issues can be divided up in two areas: medicine and field exposure.

4.2.1.1. Medicine. Metrology is expected for the emerging thematic of ambient assisted living (AAL) and for the development of body-worn medical RF devices and implants. AAL is based on new technologies such as wireless patient monitoring and the detection of a range of human physiological parameters (with stand-off detection) and requires checking the reliability and coverage of the RF systems. The development of body-worn RF devices such as body-worn antennas, body-area networks, and personal dosimeters for non-ionising radiation and implants (active and passive) will involve calibration benches and other facilities for exposure, EMC, safety, and functionality purposes. Metrology is also expected for therapeutic (hyperthermia and targeted drug delivery) and medical diagnostic techniques (radio frequency identification (RFID), implant communications, RF imaging, and magnetic

resonance imaging (MRI)) based on electromagnetic radiation up to THz for the characterization of magnetic nanoparticles (including chemical, morphological, structural, and magnetic properties) applied to applications in enhanced MRI imaging, hyperthermia, and targeted drug delivery.

4.2.1.2. Field exposure. Future metrological needs for the measurement of human exposure to EMFs are expected in a variety of diagnostic and therapeutic techniques based on the use of EMFs (figure 9). That includes RF exposure for microwave treatment and cancer therapy, magnetic hyperthermia for tumour ablation and magnetic transcranial stimulation, and EMC of medical equipment (close-proximity effects). Field exposure experiments and dosimetry for bioelectromagnetic interaction research from DC to THz are needed at the metrological level for establishing reference numerical models of the human and reliable data sets. These experiments include reliable and traceable measurement of physiological properties such as electrical conductivity or permittivity of tissues in the human body but also density, blood flow, thermal properties etc. This will be helpful for the analysis of human voxel models for EMF simulation. The exposure of the general public to, respectively, DC/LF and RF fields might also require future metrological means about the existing implementation of high-voltage transmission lines including high-voltage DC and the fast growing development of communication services (compare the airport situation—superposition of

multifrequency exposure and radar, TV and radio stations, car radar, car-to-x communication, in-flight communication systems), respectively.

4.2.2. Environment. New developments in electrical metrology over the RF to THz range are being driven by environmental policies (monitoring and security), earth observation, air monitoring for pollutant, and the science of climate change.

The key applications of the growing field of THz technology include undoubtedly the air monitoring of pollutants and the science of climate change. For example, the chemical radicals in the atmosphere have a very interesting spectral signature and particularly the chemical compounds responsible for the destruction of the ozone layer. THz spectroscopy is developing rapidly but is still often only under laboratory conditions and presently suffers from lack of reliable measurement techniques and standards in this frequency range where the developed metrological chains in microwave and infrared domains overlap with difficulty.

The need for accurate RF and MW measurements in the 60–500 GHz region to support earth observation and climate monitoring is becoming increasingly important within Europe, pushing radiometry, noise, and other measurements to their limits as laboratory specifications are required in space and *in situ* across the globe. Furthermore, multi-parameter distributed measurements for providing environmental monitoring (regulatory) and security (e.g. detecting toxic aerosols in air) are also emerging. There will be growing requirements to measure security scanners, both the electromagnetic exposure (safety limits), and performance analysis (comparison of different scanners).

EMFs are also seen as being an impact pathway associated with the construction and operation of marine energy generators (MEG) for which the potential effects on sensitive marine wildlife receptors is not fully understood. The implementation of improved underwater EMF measurements methods will support the implementation of the EU Marine Strategy Framework Directive (MSFD) [120] and foresees better knowledge of the impact of the anthropogenic introduction of energy in seas.

4.2.3. Energy. Faced by limitations in our carbon-based energy resources and the effect of these resources on our environment, there is an enormous drive in society to make our energy supply and our energy use more sustainable [121]. Important elements of the resulting energy transition are increased electricity supply via renewable energy sources, more active consumers of energy, and transformation of the electrical grids into smart grids in order to balance energy supply and demand. In this transition, the continuity and quality of electricity supply must be guaranteed or even further improved given the strong economic and social dependence of our society on our electricity supply. Scarcity of resources furthermore demands efficiency in the whole chain of supply, transmission, distribution, and utilization of electrical energy, and strongly stimulates measures leading to energy saving. Sporadic generation from renewables requires consumers to alter their behaviour to utilize available energy and

scale-back use when energy is scarce; measurements have an important role to play in future demand management. Four targets characterize the scope of activities. They are dedicated to (i) network power quality tools, (ii) *in situ* and complex power measurement, (iii) energy saving and efficiency, and (iv) improved tools for grid monitoring and control (details are given in appendix C).

4.3. Innovation

Electrical nanometrology and metrology for the RF to THz frequency range are the two branches of activities envisaged within this innovation strand and which belong both to targeted programs on broader scope of SI and industry.

4.3.1. Nanoelectronics and nanomagnetics. The lateral dimensions of devices in micro and nano-electronics are rapidly scaling down to the few-nanometre range and will ultimately reach the single atom/single molecule level. In this range, electronic, magnetic, and other physical properties of materials and devices significantly differ from bulk material properties. One reason for this is that with decreasing volume the role of interfaces and defects becomes dominant over the crystalline bulk-properties. Furthermore, quantum effects resulting from size or charge quantization become relevant leading to radically different physical properties. Mastering and controlling the device and material properties on the nanoscale is one of the great challenges of nanotechnology.

The reliable and traceable measurement of the electronic and magnetic properties of nanoscale devices and materials is the first prerequisite to enable any future research, development, and application of advanced nanoelectronic and nanomagnetic devices for at least three of the key enabling technologies (KET) identified by the European Commission (nanotechnology including bio applications, micro and nanoelectronics, and advanced materials) and considered as a major driver of economic growth in Europe. Advanced metrology for metallic, magnetic, and semiconducting nanomaterials and nanodevices are the key to underpinning the reliable research and development of advanced high tech products and devices for ICT (nanoelectronics, spintronics, sensors), medicine (bio-sensors, lab on a chip) and energy (photovoltaic (PV), energy harvesting) lead markets [122–125]. In this respect, the need for nanometrology in EM has been clearly expressed within the Nanoelectronics Standardization Roadmap by the Technical Committee TC113 of the International Electrotechnical Commission (IEC) [126, 127].

Specifically, graphene is a material which has received a lot of interest in the last decade because of its unique range of properties. The European Commission has launched a large 1-billion-euro flagship graphene project to realize a European graphene industry over a time span of 10 years. Potential applications range from aerospace to ICT and from energy to healthcare. These applications cannot be realized without the underpinning metrology from the European NMIs.

The scope of activities (described in appendix D) deals firstly with traceable measurement tools and methods allowing for the

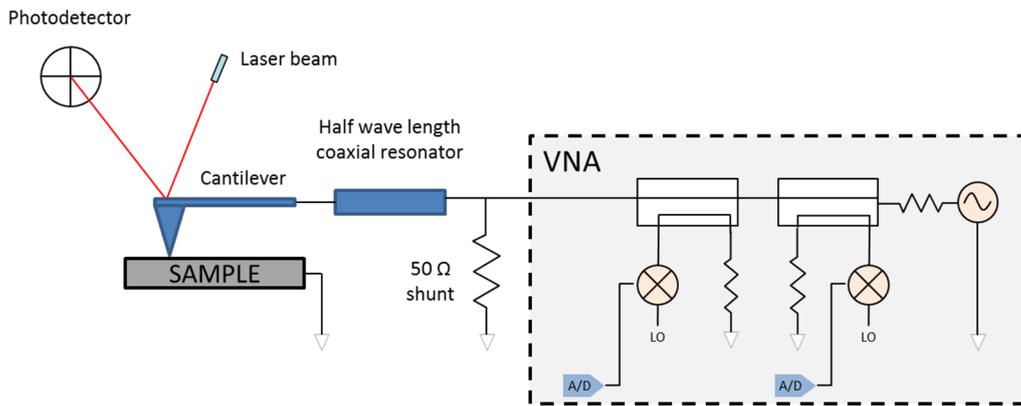


Figure 10. Scanning microwave microscope for quantitative capacitance and impedance measurements at the nanoscale [128]. Courtesy of Alexandra Delvallée (LNE).

reliable characterization at the nanoscale of materials and devices used in today's electronics (figure 10) and sensor devices, then with characterization tools for beyond CMOS technology.

4.3.2. Electrical metrology for future applications of complex RF to THz systems. Economic, demographic, and socio-cultural developments in a rapidly changing society drive new and improved ICT for advanced industrial production and quality testing (figure 11), but also for health care and environmental monitoring (see 4.2.1 and 4.2.2), security, and traffic management. This topic undoubtedly requires underpinning electrical metrology in the RF to THz range. Smart architecture, highly integrated systems, intelligent systems, near and far field communication, virtualization, multimedia applications, decentralized automation, and peer to peer collaboration are some of the buzzwords related to actual and future technical implementations. The common trend in all these developments is the increasing complexity of the systems and the increasing rates of data exchange [129]. Metrological support is needed to assure the reliability, safety, and efficiency of the technologies and to cover higher frequencies in the electromagnetic spectrum. Metrological support is even imperative to enhance the competitiveness of the European industry in the RF to THz sector and to lead the European economy into a bright future.

Activities will focus first on the multi-parameter characterization of a range of RF systems, then on metrology to be implemented for large-scale fully automated complex RF systems (see details in appendix E).

4.4. Prenormative

The large energy sector as well as the high-frequency domain for communication systems, EMC testing and the field of nano-electronics involve prenormative activities.

4.4.1. Power and energy and smart grids¹⁰ [131–134]. Given the importance of a reliable electricity supply there is an enormous number of written standards available and still under development in the area of power and energy measurements

¹⁰ See the references to the CEN, CENELEC, and ETSI smart grid standardisation activities on the CENELEC web page [133].

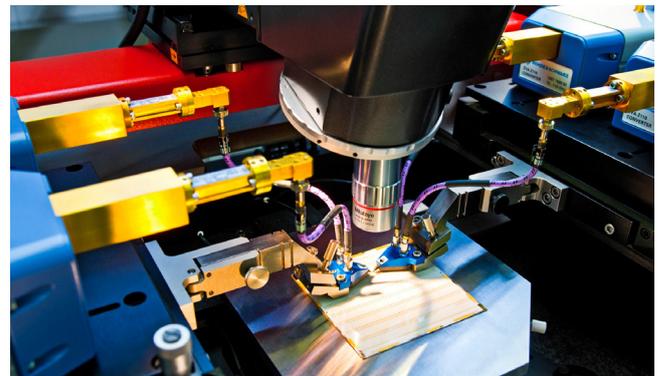


Figure 11. Differential S parameters for planar circuits [130]. Courtesy of Rohde & Schwarz.

and smart grids. Internationally, these activities are driven by among others, i.e. the IEC, International Council on large electric systems (CIGRE), European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC or CLC), and European Telecommunications Standards Institute (ETSI). In smart grids, the standardization bodies CEN, CENELEC, and ETSI¹⁰ have joined forces in Europe for a systematic and sustainable standardization of smart grids in order to fulfil the ambitious energy policy targets around the world. This is supported by a strong political drive for the realization of a single market for gas and electricity.

Metrologists from NMIs are already actively involved in these standardization activities related to measurement and data security via active participation in standardization technical committees, among others IEC SC77A, CIGRE SC D1, IEC TC38, and IEC TC42. Metrologists active in the EMRP JRP 'smart grid metrology' are active observers of the activities of the CEN-CLC-ETSI Smart Grid Coordination Group (SGCG), and participate in their meetings and some of the task forces coordinated by the SGCG. They also provided feedback to the 2011 strategic report outlining the standardization requirements for implementing the European Vision of Smart Grids. Finally, contacts are maintained with NIST which in the US has the same role as the SGCG in Europe.

It is expected that these activities will be further intensified since for example smart grid monitoring and control,

energy measurements, and energy saving all strongly rely on the availability of reliable measurement data. The envisaged role of the metrology community is to scrutinize draft international standards for measurement issues and where necessary develop methodologies and physical standards to enable practical and robust measurements in support of regulation regimes that emerge from standardization. They should ensure that the impact of inaccurate measurements is assessed and where necessary the requirement for traceable calibration is incorporated into standards.

4.4.2. Communication systems and EMC testing. ETSI produces globally applicable standards for ICT, including fixed, mobile, radio, converged, broadcast, and internet technologies. But, some of the standards (e.g. ETSI EN 305 550 40–243 GHz, generic short range devices) require measurements which are not available at all. All near-field communication (NFC) systems including RFID [135–137] and the varied broadband (THz) communication systems require research prior to standardization. Besides communication technology, the area of EMC testing (e.g. the documents of the International Special Committee on Radio Interference (CISPR)) also involves pre-normative works. In the current EMRP, the ongoing EMC JRP relating to round robin standards could be considered as pre-normative. As for basic RF&MW quantities there are some normative documents relating to interconnects and transmission lines.

4.4.3. Nanoelectrotechnics. In 2010, CEN/CENELEC accepted the M461 mandate from the European Commission to elaborate normative documents around nanomaterials and nanotechnologies. For this, the relevant technical committee CEN/TC352 (‘nanotechnologies’) is developing standards in a liaison with the International Organization for Standardization (ISO/TC 229 ‘Nanotechnologies’) and IEC (IEC/TC 113 ‘Nanotechnology Standardization for Electrical and Electronic Products and Systems’) generally along the three action plans: (i) terminology and nomenclature, (ii) measurement and characterization, and (iii) evaluation of performances including reliability and durability.

Taking into account the first roadmap recently drawn up by IEC/TC113 and focused in priority on nanomaterials and nanodevices for applications in ICT and electronics (within ‘More Moore’s priorities), pre-normative metrological works are expected in the field of electricity and magnetism (but not only) for nanomaterials such as graphene, nanowire (III–V, II–VI, ZnO) and nanoparticles in general (e.g. electrical characteristics related to size, crystal structure, and composition). Pre-normative works are also needed about the electromagnetic properties and performances of nanoscale devices (nanoelectronic, nanomagnetic, and molecular devices), for scanning probe microscopes including electrical SPM with a strong expectation regarding the current issue on nanoscale contacts and interconnects, or for instrumentation based on other tools such as nano-electro-mechanical systems (NEMS). Guidelines to make reliable measurements of nanoelectronics and spintronics are among the targeted achievements of some ongoing JRPs. These works could be considered as a first step towards standardization in these fields.

5. Conclusion and outlook

EURAMET activities both in R&D within the EMRP programme and in the management of CMC for the CIPM MRA have been reviewed. In summary, EURAMET leadership has been maintained in fundamental metrology over the last decade thanks to the remarkable results obtained for example on QHE in graphene, tunable barrier electron pumps, and AC electrical metrology based on Josephson devices. Tremendous efforts were made on fundamental testing (quantum metrology triangle, universality test on QHE) and the determination of fundamental constants (h , e , and the fine structure constant α) placing some EURAMET NMIs at the forefront of the revision of the SI. For low frequency quantities, EURAMET NMIs continued developing capabilities to efficiently support stakeholders involved in the pioneering decision of EU towards the energy transition: generation (including harvesting), distribution (smart grid), storage, and consumption. In the domain of high frequencies, a more solid traceability to SI units was established in fundamental measurement quantities with a push to higher frequencies (THz). In addition, extending the range of capabilities is on track to deal with emerging ICT issues and human exposure to EMF. The rationalization of the CMC structure together with an analysis of the time-based evolution of traceability sources declared in the CMC entries, and the joint management of comparisons including the development of an online comparison Toolbox, are the main EURAMET TC-EM contributions aimed at making the CIPM MRA sustainable.

Based on the success of the EMRP with a higher level of cooperation between EURAMET members in research activities a new European metrology program, EMPIR, has been launched in 2014 and will continue for a period of ten years. We have outlined the activities planned in EM along the four axes:

- Fundamental scientific metrology, from practical realization of the definition of electrical units in the revised SI to quantum enhanced electrical standards.
- Grand challenges, in priority energy where low frequency electrical metrology remains an important field, but also health and environment with planned contributions in high frequencies up to the THz regime.
- Innovation with two proposed (industry-oriented) activities, the electrical and magnetic metrology at nanoscale and metrology for RF to THz frequency range.
- Pre-normative along three identified branches: energy and smart grids, HF communication systems including EMC testing, and nanoelectrotechnics.

On the basis of JRPs which have been selected for funding at the first three EMPIR calls (2014, 2015, and 2016), the EM remains a very prolific domain and contributes to most of expectations of the programme [138].

Within EURAMET, the discussion is starting about the follow-up of EMPIR which could be proposed to the EU for the period 2025–2035 and within next years, European metrologists will be asked again to give their thoughts on future activities by drawing up new roadmaps. The societal

and industrial needs in EM metrology envisioned for this next decade will be embedded in the context of permanent great challenges such as energy transition, health, and environment, and in a transition period between the industry 3.0 and the ‘digital’ industry 4.0. Most of the activities planned for the current period will remain relevant in the decades to come.

Electrical metrology will continue to support the generation, storage, control, and distribution of electrical energies which are strongly expected to increase. This support includes the development of the renewable energies converted in electricity and which should take precedence over fossil energy. Metrology in EM will be also indispensable for the emerging technology of the internet of things (IoT) which rely on (virtual) sensors, low power communication and energy harvesting, novel RF communication based on ‘beyond CMOS’ technology. It is noteworthy that EM metrology has already supported the development of RFID which can be seen as a forerunner of the IoT. For example, self-driven (electrical) vehicles connected to a smart electrical grid and fitted with RF communication sensors enabling interaction with other vehicles (anti-collision systems) and the road itself would undoubtedly need to be underpinned by electrical metrology. Metrology in EM is also expected to be at the core of smart factories through sensors and renewable electrical energy supplies [3].

Correlated to IoT technology in the revolution of the digital industry, the new concept of ‘big data’ will also generate some metrological issues. A crucial error would be to consider that working on a large amount of data would necessarily affect the accuracy of the results and consequently we would have to *learn to sacrifice accuracy to achieve results* (allowed by this large amount of data) *that we have never had before*. Of course, metrology will remain indispensable at least to provide references and to master and correct the errors which impact the reliability of the data. The theme of smart grids and ambient assisted living are examples which will raise big data issues in electrical metrology.

Finally, quantum electrical metrology will take a natural place in the emerging quantum technologies from quantum standards towards quantum instrumentation and likely towards quantum information and quantum computing. For the latter, according to reference [139], human-friendly control systems would have to be designed in order to prevent ‘the possibility of quantum computing with artificial intelligence and sensor networks growing beyond human control.’ Again the development of such control systems would be underpinned by electrical metrology.

In any case, there are certainties on the continuation of the key place of EM in metrology in the future. EURAMET, like the other RMOs, will pursue its efforts in that domain to meet the requirements of society and industry as much as possible and in the most efficient way.

In a world increasingly facing challenges on a global scale, the international coordination of the research efforts in metrology become indispensable. In a future metrology programme networks of excellence will ideally be established, where metrology experts will be able to work and interact without the limitations of national or organisational barriers.

The challenge is to involve all players in such a development. Capacity building will continue to be a key activity for EURAMET, where its members are active in defining their roles in the research coordination. Further steps towards better integration will include the coordinated planning and sharing of special research facilities to avoid unnecessary duplication as well as the creation of European networks of competence in metrology research, bundling of de-centralised competence in a network of researchers, and institutions working on a thematic focus.

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Appendix A. EMRP joint research projects in EM

Of the 140 JRPs that have been funded, 33 were in the field of EM. A success rate of 62% was reached in the selection process (20 proposed JRPs in EM were not selected). These good results can be explained by the already great mutual understanding between the labs in EM, built within EUROMET, and common past experiences in previously funded European research projects. Figure A1 shows the funded JRPs broken down into three sub domains: fundamental metrology (quantum standards, Kibble balances etc), LF quantities including power and energy, and RF and microwave area [140]¹¹. The reader who might be interested in one of these EMRP JRPs can find the relevant information (consortium, working program, reports, and publishable summary etc) on the EURAMET website or on the project website itself.

Beyond the successful scientific and technical achievements, a preliminary overall assessment of these JRPs has been found encouraging in terms of statistics:

- The first positive feature is the composition of the JRP consortia. Almost all the EURAMET NMIs have participated in the EMRP projects in the field of EM. There were also two NMIs from another RMO (APMP—Asia Pacific Metrology Programme), and above all a significant number of academic laboratories (59 organizations) which in fact resulted in the historical links between the metrology community and the academic sector. This positive picture is marred by the small number of industrial

¹¹ It must be noted that common to these three groups, five JRPs were fully or partly dedicated to nanometrology (nanospin, MetMags, MetNEMS, EMINDA and SolCell).

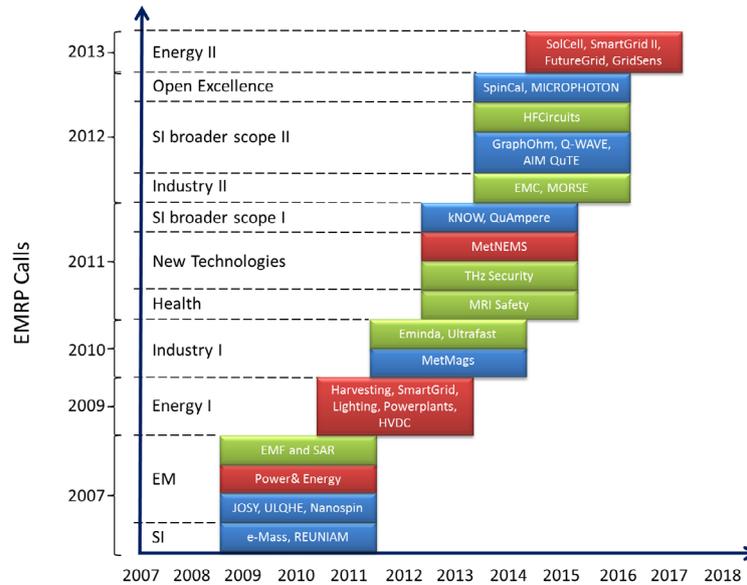


Figure A1. Repartition of the JRPs founded in EM within EMRP calls according to their own domain (blue: fundamental metrology, red: low frequency domain, green: RF and microwave). The JRPs are listed by their acronyms. See the full name and description in reference [135]. For clarity, the subcalls dedicated to environment in 2010 and 2013 (for which no JRP was proposed from the EM community) are not shown.

partners (14 different organizations) which were involved in these JRPs. However, the latter have had an impact on the industry through 189 inputs to standard committees (94 standard committees engaged with these inputs) and 10 patent applications.

- Considering the output data provided by the JRP coordinators in their reports and collated by the end of 2015, the strong impact of the JRPs in EM for science and society is reflected in the number of peer-reviewed publications, more than 300, and 1000 conference presentations. Even more remarkable is the promising level of cooperation between partners with a ratio of 30% of these papers co-authored by two different NMIs (that ratio increased up to 50% for all partner types). The cooperation level can also be reviewed from the training activities internally between the consortium members. Around three internal training activities per JRP have been reported so far.

Appendix B. Quantum electrical metrology

The activity plan in quantum electrical metrology is composed of four targets described below.

B.1. Practical realization of the new definitions of the SI units according to CIPM recommendations [115, 116] This scope covers the practical realization of the new definitions of the kilogram, the Kelvin, and the ampere, which will be linked to the Planck constant h , Boltzmann constant k , and the elementary charge e , respectively. It comprises in priority the realization of the quantum ampere through the development of quantum meters and sources (nanoampere self-referenced quantum current sources with integrated SET detectors, quantum current scaling, low-noise quantum

current amplifiers etc) and the improvements to the QHE and SET by using new materials (i.e. graphene). The improvement of the Kibble balances to make the linking of the kilogram to h more reliable, accurate, and practical and the development of quantum noise thermometry to realize the Kelvin by a quantum method for implementing Josephson devices [141, 142] are highly desirable.

B.2. Fundamental consistency tests in electrical quantum metrology and determination of fundamental constants [115, 116, 143] This work will focus on studies of SET in different semiconducting and metallic devices and on novel quantum resistors (graphene). Experiments to verify the quantum metrology triangle will be continued. Next generation experiments will be developed to determine improved values of fundamental constants. Calculable capacitors will give a value for the pivotal fine structure constant α to be compared with that from atomic physics. These measurements will also yield values for R_K in the present SI and the electric constant ϵ_0 in the future SI. Similarly, the Kibble balance experiment provides a key link between h and the kilogram in our present and future SI systems. Determination of the shielded proton (or Helion) gyromagnetic ratio $\gamma_{p,h}$ widely used for tracing back the magnetic field measurements (NMR sensors) to the SI could be also investigated. It must be noted that this constant will be the least well-known on the list of electromagnetic constants in the revised SI with an expected uncertainty at the level of part in 10^8 .

B.3. Simplified 'fit for purpose' calibration tools and intrinsically referenced calibration systems tailored to customer needs The quantum standards will be based on large-scale integration of semiconductor, graphene, superconductor, and single-electron technologies. DC and AC standards of voltage,

current, and impedance in a wide range of magnitude and frequency will be made available together with quantum traceability for digital electrical measurements including general purpose DC/AC bridges. The scaling instruments with self-calibrating capabilities will include quantum ratiometric DC and AC standards (based on Josephson and Hall devices), superconducting DC and AC current comparators, and high-accuracy mixed-signal electronics. It is expected that simple and transportable quantum standards will be developed as well as a liquid-He free turn-key (U , Z , I) quantum calibrator covering extended scales and arbitrary signals.

B.4. Metrology for solid-state quantum engineering and quantum enhanced electrical SI standards [117, 118] Novel solid-state technologies based on quantum effects require metrology beyond the present SI. These technologies refer to a wide range of quantum solid-state devices: superconducting systems (Josephson or SQUID parametric amplifiers [144–148], superconducting resonators [149, 150], superconducting wires acting as quantum phase slip junctions [151] etc), semiconductor quantum dots [152], spintronic devices [153], or hybrid quantum circuits involving nitrogen-vacancy centres in a diamond crystal [154].

Traceability and comparability need to be established for solid-state quantum measurements so that once validated these measurements will allow reliable fidelity testing of quantum devices. The work towards this scope relies on measurement techniques that characterize the quantum state of a solid-state based system. Techniques for the controlled preparation of quantum states are a prerequisite for the development of elaborated measuring techniques. Because electromagnetic signals from quantum systems are usually small, amplification techniques with minimal back-action need to be developed to routinely approach the standard quantum limit. Development of measurements based on parametric effects and bifurcations in nonlinear systems can substantially improve the fidelity of readout of some macroscopic quantum objects [144–150]. Entanglement is a powerful resource to perform quantum enhanced measurements that are not possible relying only on classical physics. The quantum strategies will be exploited to increase the sensitivity and accuracy of electrical measurements leading to quantum enhanced electrical standards. Entanglement of quantum objects of different nature, control of quantum mechanical coupling, squeezing of quantum states [155, 156], and quantum non-demolition strategies [157] for measurements are among the concepts exploited to this end.

Appendix C. Energy

The four targets that characterize the scope of TC-EM energy activities under EMPIR are given below in chronological order.

C.1. Network power quality tools Understanding the propagation of power quality events over a wide area is important to the management of a stable and reliable electricity supply. Multipoint geographically distributed network PQ

measurements are needed together with network models to determine areas where the grid requires reinforcement, such that new renewable generation capacity can be safely integrated without degrading PQ.

C.2. *In situ* and complex power measurement. Whilst traditional 50 Hz sinewave power measurements can be made with high precision, *in situ* and complex power measurements are required to meet the challenges brought about by emerging smart grid technologies. Complex power measurements in the presence of high distorted, pulsed, wideband and fluctuating waveforms are required at power levels ranging from micro-power energy harvesting devices to megawatt level power converters. Distributed networks require on-site calibration and verification of settlement meters and smart meters.

C.3. Energy saving and efficiency The most significant carbon savings can be achieved through energy saving and efficiency improvements at each point in the electricity supply chain from generation, through distribution, to the appliances that use the power. A renewable generation plant requires *in situ* measurement of power for performance assessment. Low loss energy transmission systems and ultra-efficient electrical machines require loss measurements. Energy saving appliances and electric vehicles need power measurement to verify and iteratively improve design.

C.4. Improved tools for grid monitoring and control Grid monitoring and control is vital to the stable operation of the network both at transmission and distribution level. The integration of unpredictable renewable generation capacity and the advent of distributed smart grid networks are significant control challenges compared to the traditional passive electrical supply system. Grid instrumentation such as PMU and a network of nodal power flow sensors will be increasingly used to determine the system state. Uncertainty-based methodologies are required to direct the configuration and accuracy of these sensor networks. Vast quantities of data will need to be processed and assimilated to provide actionable information for network controllers, such that the network can be protected from instability and blackouts.

Appendix D. Nanoelectronics and nanomagnetism

The scope of the activities described below is composed of two issues: (i) characterization tools for today's electronics and sensors, and (ii) characterization tools for beyond CMOS technology.

For today's electronics and sensors, present microscopy tools (scanning probe, optical, electron beam etc) allow for the measurement of the spatial dimensions of nanoscale devices and materials with high resolution. Furthermore, surface science methods allow for the measurement of surface properties and composition. Also many EM properties of materials and devices can be measured on the nanometre scale [158]. However, at present the traceability of the above measurements is only very partially ensured.

CMOS technology is based on the control of the charge state of nanostructured semiconductor nodes. The presence or absence of electrical charges or currents represents the digits '0' and '1' in information processing and storage. CMOS technology is expected to extend beyond this paradigm in two ways: on the one hand, properties other than electronic charge could be exploited for information processing (e.g. the spin of electron exploited in the emerging field of spintronics [153]); on the other hand, advanced material systems (such as graphene, carbon nanotubes, magnetic semiconductors, metamaterials, molecular devices) might allow for improved device performance and scaling.

D.1. Characterization tools for today's electronics and sensors

A large variety of EM properties are relevant for device operation, among them conductance, conductivity, complex impedance, transconductance, magnetization, and others. Such EM properties are generally directly related to more fundamental material properties such as doping density, spatial dimensions, and surface passivation etc. Therefore a traceable measurement of these fundamental properties is also required and must be taken into account for in the assessment of the measured EM properties and their uncertainty. Here the development of functional traceable microscopy, including metrological electrical and magnetic SPM, and measurement tools will allow traceable measurements of EM properties on the nanometre scale. Transfer of traceability to industrial stakeholders will be ensured by the development of suitable reference materials allowing for the calibration of industrial characterization means in the stakeholder's facilities. In addition to nanometre-scale spatially resolved EM measurements the characterization of the high bandwidth response of materials and devices is essential to fast device operation. Here high bandwidth measurements in combination with suitable modelling will allow for the development of comprehensive high-frequency EM reference materials which, in turn, will allow for the traceable characterization of high bandwidth EM probes.

D.2. Characterization tools for beyond CMOS technology

For both beyond-CMOS paths (spintronics and advanced material systems) new traceable EM measurement tools and methods will have to be developed. These will enable in particular traceable EM measurements (including imaging) of advanced properties such as spin polarization, thermoelectric and thermal transport, spin Hall transport, spin currents or stray field distribution, and generation and detection of spin-waves, magnons, and optical excitations. These new tools and methods will require the highest sensitivity to reliably probe the small sample volumes of nanoscale devices and materials. Ideally, extended multi-functional or reconfigurable probes will allow for the access to different key properties of future beyond-CMOS devices and materials. Their integration into scanning tools for advanced material and device properties can allow for high spatially resolved mapping of these key parameters for device and material development and quality control. Again traceability will have to be ensured by suitable reference materials and guidelines for the traceable

characterization of advanced material properties which will be made available to the stakeholders. In a more general way, a highly focused metrological framework is considered as essential to underpinning advanced device and material development for applications such as sensors, actuators, ICT, and biotechnology. For example, graphene and other 2D material specific characterization tools are highly desirable for their electrical, surface, chemical, and mechanical properties.

Appendix E. Electrical metrology for future applications of complex RF to THz systems

The envisaged activities are focused on two targets as described below.

E.1. Multi-parameter characterization of RF systems As the use of smart and reconfigurable antennas continues to grow with wireless technologies becoming ubiquitous, there is the requirement to provide efficient antenna calibration algorithms, such as near-field to far-field transforms and rapid pattern-testing methodologies. Propagation effects to determine the characterization of radio channels with multiple-in, multiple-out systems (MIMO) systems become important, as does the need to provide EMF scanning to verify signal paths, and to validate antenna models and interference paths in new situations and applications (for example wind turbine versus radar, intelligent transport systems, vehicle to vehicle communications). The determination of propagation effects in wider frequencies, such as the THz range, will also be required for a range of parameters.

New demands from leading-edge high-frequency industrial electronics applications require multi-parameter high frequency measurements in a range of situations both in the laboratory and on-site, such as high-speed differential measurements, electronic calibration units, balanced and unbalanced measurements, and on-wafer. Needs for multi-parameter on-wafer measurements of next generation devices are also emerging. Underpinning metrology is required for automatic calibration and self-validation for on-site measurements, to provide confidence in advanced RF technological systems.

The range of complex measurements expected in both the time-and-frequency domains will continue to grow, for example microwave and EMC antenna measurements, communications instrumentation, and power flux density measurements, including spatial resolution. In all cases the propagation of uncertainties between the domains (e.g. transforms, correlations, covariance matrices) continues to be of importance and must be addressed, with specific challenges for communication parameters such as modulation signal parameters and error vector magnitude.

Finally, the use of microwave and THz imaging will grow to enable industrial processes to be monitored on-site, semi or fully autonomously, and be integrated with distributed sensors to provide quality control, improve efficiency, and satisfy health and safety.

E.2. Metrology for large-scale fully automated complex RF systems Within the coming decades, the development of large-scale, fully automated and complex systems in the microwave to millimetre and sub-millimetre wave frequency range is expected. Metrology must support this development by adequate measurement methods, calibration capabilities, and traceability to SI units. This will be accompanied by both continuously increased frequency and dynamic ranges of RF physical quantities on the one the hand and the usage of multiple physical quantities by sensor and data fusion on the other. Automatic calibration, validation, self-referencing, and error-correction methods will greatly improve the safety, security, and availability of systems. Validated benchmarks and complex on-site measurement systems are required to underpin confidence in the functionality of highly advanced RF technological systems. Automated expert systems facilitate the design, installation, operation, and quality and conformity assessment of such systems.

The next-but-one generation of short-range communication systems will make use of frequencies up to 300 GHz. Due to short-wave propagation effects these frequencies behave like optical waves including blocking, reflection, diffraction, scattering, and bending. Furthermore, the transmitted power may be limited to avoid health effects and to take safety limits into account. Therefore, new concepts for wave direction and re-routing in automated and reconfigurable networks are expected to enable ultra-high data rates with extremely high operational availability.

Industrial processes may also be reconfigured according to lean production and facility management. Sensor networks over-the-air will replace hard-wired cabling to be in line with modern production scenarios also addressing new and rapid production roll-outs. Automatic means of transportation are envisaged making use of precision 3D-localization systems.

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