“Big” Problems in Electromagnetics

CCEM Strategic Planning Document

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This document is a product of the Consultative Committee for Electricity and Magnetism's (CCEM) Working Group on Strategic Planning. The Working Group was formed to both identify the major future problems challenging the National Metrology Institutes in electromagnetic metrology and to provide input to the CCEM on the BIPM's technical program on electrical metrology. It is in its former role that this document was created. Identifying the major challenges in electromagnetic metrology serves many purposes. One is as input to the strategic planning occurring at the world's NMIs and also being undertaken by some of the Regional Metrology Organizations. As resources are being directed to nanometrology, chemical metrology, and biometrology, it is important that electrometrology continues apace as many of the measurements in the new areas will depend upon accurate measurements of electromagnetic properties under challenging conditions. Many of the problems identified in this document are large in scope and demanding on resources. By their nature they will require many of the world's NMIs working together to achieve success. This document then identifies areas where international collaborations should be focused.

The document outlines first specific technical measurement challenges facing the electromagnetic metrology community. It ends with societal problems that require the attention of this community for solution.

The Working Group included all major electromagnetic measurement challenges not just those traditionally considered by the CCEM.

It is understood that this document is a work in progress. The Working Group attempted to look in the future to identify the important problems on the 5 to 10 year horizon. Undoubtedly, the Group missed some and in the next several months and years the document will need to evolve to capture the reality of the day.

We hope the CIPM, the CCEM, the RMOs, and the NMIs find value in this document,

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Technical Challenges

Single Electronics

While much progress has been made, it remains a significant challenge to extend our fundamental understanding of single electron tunneling (SET) physics and to realize the goal of building novel integrated circuits that precisely manipulate and detect individual electrons. Single electronics is a “big problem” due to 1) extreme sensitivity of single electrons to environmental perturbations, and 2) difficulties in controlling and eliminating electrically active defects introduced during device fabrication. The worldwide electrical metrology community needs reproducible fabrication and reliable operation of multi-junction electrons pumps with sufficient metrological accuracy for use in electron-counting-based capacitance standards and at higher currents for use in potential current standards. New measurement techniques are needed to study single electron tunneling dynamics at high speed and to explicitly characterize where and when error events occur.

Advances in single electronics will have an impact on a wide variety of application areas, from fundamental electrical metrology to nanoelectronics. For example, various classes of future nanoelectronics beyond CMOS are projected to work with one or a few electrons. These include molecular electronics, semiconductor-based integrated circuits using single-electron memory or logic, and quantum computing (QC). As another example, one endemic problem in any circuit which depends on small numbers of electrons is the "charge offset" phenomenon, which makes it difficult or impossible to integrate multiple single-electron tunneling (SET)-based devices together; this problem gets more difficult as the device gets smaller. The table below provides additional information on application areas and requirements for improvements in single electronics.

Application Area	Examples	Key Requirements	Competing Technologies
Fundamental Metrology	Quantum metrology triangle and other consistency checks.	Accuracy is paramount; affordability and usability are secondary.	None, since there is no substitute for current based on the charge of the electron, e
Applied Metrology	Calibration of electrometers and picoammeters for dosimetry, etc. Calibration of capacitors.	Combination of accuracy, affordability, and usability is important	Current obtained via Josephson voltage standard (JVS) plus quantum Hall resistance (QHR) or $I = C(dV/dt)$ Calculable capacitor or ac QHR plus quadrature bridge.

Novel Measurements	Local probe of charge transport in nanostructures. (including CMOS), studies of quasiparticles in qubits, characterization of charge-based single-photon sources, particle detectors, electric field mapping, ...	Sensitivity (and in some cases accuracy) is paramount; affordability and usability are secondary.	CMOS and other semiconductor devices; various mesoscopic systems (quantum dots, nanotubes, cantilevers, etc.)
Information Processing	Quantum-dot cellular automata (QCA) cells, spintronics, etc. (classical bits) Qubits with charge-based readout, quantum-limited amplifier for qubit readout.	Surpassing CMOS in terms of speed, usability, reliability, and affordability is difficult. It will probably require mastery of "bottom-up" fabrication. Long coherence time, controlled back-action.	Anything else mentioned in the semiconductor industry (ITRS) roadmap. Anything else mentioned in the quantum computing roadmap.

Single Photonics

The photon is one of the fundamental particles in modern physics and is the basic quantum of electromagnetic radiation. The quantized nature of photon states suggests momentous opportunities for metrology based on photonics, yet this potential has barely been exploited. Recent advances in solid-state photonics, optical detectors, and optoelectronics have yielded new techniques for the production, manipulation, and detection of single photons. The technology to take advantage of the quantum nature of the photon is becoming available, and the goal of providing radiometric measurements based on photon count is becoming realistic.

Creation and detection of single photons is difficult because of the challenges in achieving the unity quantum efficiency that is required to ensure that the photon number is accurate. Furthermore, the ability to generate and detect photons in the numbers needed to match picowatt and nanowatt powers requires significant advances in single photon generator emission rate and photon detector count rate. New measurement methods are needed to exhaustively characterize the state of photons with high sensitivity to small photon numbers.

Advances can be applied to a wide variety of technology areas. High-flux single photon sources and detectors could provide new, improved methods for optical radiometry and the calibration of optical power meters. Fock state sources could be used to demonstrate interferometry and lithography with resolutions beyond that of classical limits (1/N rather than 1/√N for N photons). In the non-classical photon states, the phase noise can be considerably reduced because it is inversely proportional to the photon number. This will lead to a new length scale with lower uncertainty. High-rate single-photon sources and detectors could enable secure quantum key distribution systems over optical fibers or free space.

Many NMIs began to work on the development of non-classical light sources such as single photon sources or correlated photon pairs. Photon measurement techniques are also being developed; such as a single photon detector (SPD) and photon number resolving detectors (PNRD). Especially PNRDs can reveal the nature of the photon distribution in non-classical light. In industry, these techniques are going to be used in the quantum key distribution, which is based on using single photons to ensure truly secure communication.

Therefore, the technology of creation and measurement of photons will definitely play an important role in metrology. International collaboration in this field is indispensable to boost the research and development.

Application Area	Examples	Key Requirements	Competing Technologies
Fundamental Metrology	Detection and creating of single photons.	Non-Poisson generation of photons. Accurate detection. Affordability and usability are secondary.	Avalanche photodiodes have high dark counts. Parametric conversion is Poisson-like.
Applied Metrology	Calibration of cryogenic radiometers, detectors.	Ability to measure or generate high photon flux at near single photon precision.	none
Novel Measurements	Heisenberg-limited interferometry.	Creation of indistinguishable photon Fock states.	none
Information Processing	Quantum key distribution (QKD).	High rate single-photon-on-demand sources; high-bandwidth single photon detectors.	Attenuated lasers and avalanche photodiodes (APDs), but QKD is not provably secure with these devices.

Quantum Voltage

The development of quantum voltage standards based upon Josephson junction technology has revolutionized voltage metrology around the entire world. New direct comparison techniques now allow for determinations of voltage better than a part in 10^9

for dc applications. There remain essentially 2 primary challenges in the realization and dissemination of voltage: 1) development of a simplified system to allow for the extensive and common place usage of quantum dc voltage standards; and 2) development of quantum voltage standards for ac and arbitrary waveform applications. The first challenge is difficult because it requires significant development of array technology, microwave integrated circuits, electronic instrumentation, and cryogenic packaging to produce a truly reliable universally applicable system. The second area is even more challenging because quantum standards would be useful over such a broad parameter space of voltage magnitude and frequency. Successful development of a "universal" voltage standard will require significant advances in all design, fabrication, and engineering aspects of an arbitrary waveform Josephson voltage standard (JVS) system.

Advances in the development of improved JVS systems will impact many technical areas related to electrical metrology. For example, "turn key" quantum voltage standards will require improved cryocooler technologies. Future systems require higher voltages for both dc and ac applications that depend upon advances in chip fabrication for increased voltages and better operating margins. As ac systems are developed for extended frequency ranges, improvements in the bitstream generators will be required, as will improvements in the techniques for transmitting the precision ac signals. The solution of these challenges will advance all voltage metrology as the world continues to develop new quantum voltage systems.

Application Area	Examples	Key Requirements	Competing Technologies
Fundamental Metrology	Universal and common realization of voltage.	Accuracy, affordability and usability are all critical.	None, since Zener diodes have inherent uncertainties.
Applied Metrology	Development of quantum standards for ac-dc difference and electric power. Applications as calibrators for oscilloscopes, samplers, and sources.	Combination of accuracy, affordability, and usability is important.	Traditional signal generators combined with traceability to other standards.

Electronic Kilogram

The goal is to develop a synthesis of mechanical, material, electromagnetic, computational, and quantum technologies that will become the national kilogram mass standard reference for the foreseeable future. To create a standard reference, all these technologies must be incorporated with absolute traceability to references for the second, meter, volt, and ohm. This traceability, along with stability and reproducibility, must be maintained at better than the part in 10^8 level in order to accommodate the commercial and scientific needs of the world. With the likely redefinition of the kilogram and assignment of the Planck constant, the volt and ohm will become fixed and independent of the kilogram, but all commerce and scientific measurements related to mass, pressure, and force will be impacted by the electronic kilogram standard.

The challenge is to achieve electronic kilogram systems that can be flawlessly, efficiently, and continuously operated in several locations around the world. The difficulty in this problem arises in the long-term reproducibility at the high precision required for establishing kilogram that is constant over the next decades. At the part in 10^8 level, many external environmental effects and internal mechanical or electrical properties are not negligible. Since the resulting standard is an absolute measurement as opposed to a relative measurement, these effects must be characterized (e.g. alignment corrections, gravity acceleration), reduced (e.g. vibrations and radio-frequency interference), or measured such that the effect cancels with the proper experimental procedure (e.g., both the magnitude and drift in the magnetic field, and also heat energy and friction energy losses are eliminated in the dual mode method of the watt balance technique). Some examples of advances needed to make the electronic kilogram a reliable national standard include: a stable magnetic field source less costly in use of liquid helium; more stable, lower noise, and lower leakage electronics and electrical components; laser interferometry electronics that are both fast, very high precision, and accurately timed; and mass standards of materials with surfaces stable under vacuum and mechanical wear.

Application Area	Examples	Key Requirements	Competing Technologies
Fundamental Metrology	Redefinition of the SI and determination of Planck's constant.	Accuracy is paramount.	Si-sphere Avogadro experiment (still an artifact).
Applied Metrology	Realization of the kilogram.	Combination of accuracy, affordability, and usability is important.	Present physical artifacts.
Novel Measurements	Application of the most precise representation of length, time, voltage, resistance, and gravity in an experimental apparatus.	Low uncertainty, repeatability, and reliability are essential.	

Quantum Computing with Superconducting Qubits

Quantum Computing is one of the most exciting and dynamic fields of modern physics with potential "paradigm shifting" impact in areas as diverse as communication security, digital signatures, computation related to scheduling problems, and simulation of complex systems such as drug synthesis. Numerous implementations of quantum computing are being pursued each using a different physical entity for the quantum bit or qubit. Examples are atoms, ions, isolated spins in solids, and superconducting integrated circuits. The latter approach is particularly challenging, because of the difficulty in isolating the qubit from external perturbations but holds great promise because, once a single long-lived qubit is realized, integration of multiple qubits into complex circuits can be done using well-known techniques from silicon integrated circuits.

To realize a useful qubit one must 1) initialize its quantum state, 2) isolate the qubit sufficiently from external perturbations such that the quantum state can evolve undisturbed, 3) couple the qubit in a controlled way to neighboring qubits, and finally 4) read out the qubit state with high fidelity. The work addressing each of these needs has profound metrological impact as electrical (and physical) metrology evolves ever more quickly to quantum-based standards and measurements. The sensitivity of a qubit to external perturbations makes it an exquisite detector for other quantum phenomena such as single charge transport and even quantized mechanical motion. The need for isolation has spurred very fundamental research into the role of "quasiparticle poisoning" on the operation of superconducting circuits and the requirement for readout provides impetus for the development of quantum limited high speed amplifiers. Given the profound difficulty of building a quantum computer, it is highly likely that the technology developed pursuing this goal may, in fact, have its first application not in Quantum Information but in quantum-based standards and measurements.

Nano Bioelectronics

Research in the biological and medical sciences is evolving from the traditional top-down observational-based efforts on animal or cell cultures to include methods where measurements of the most fundamental processes enable the understanding of more complex processes. This change has been enabled by the development of new technologies and driven by the need to diagnose and treat disease faster, cheaper, and better for affordable healthcare.

Current optical-based fluorescence methods have high sensitivity for biological and medical research but instrument miniaturization for portable diagnostics has not yet been achieved. Electronic-based methods have the advantage of enabling portable diagnostic systems but suffer from low sensitivity for measurements of biologically relevant concentrations of analytes. With the advent of microfluidics and nanopore technologies, electronic-based methods can achieve single molecule sensitivity because of the confinement (or packing) of samples into small spaces, which results in measurable concentrations.

A major measurement challenge is to develop measurement methods that can characterize the response of single cells or small cell populations with single molecule sensitivity, and to do this for multiple analytes. To achieve this, new electronic sensors and methods must be developed. Furthermore, these new methods must be validated with the accepted fluorescence-based methods.

Advances can be applied to a wide variety of technology areas. Nanopore technology can be used to measure the structure of DNA, but it is not yet clear what detail can be resolved and if DNA can be electronically sequenced. Conductance, pH, and electrochemical sensors can also be developed and integrated amplifiers could also increase sensitivity and performance. Other new technologies include nanowires, single electron devices, and microwave transmission line technology for temperature control and detection.

Application Area	Examples	Key Requirements	Competing Technologies
Single molecule electronic detection and sequencing	Structure/function measurement of DNA and other stranded molecules: electronic sequencing.	Low current measurement, integration of biological and/or solid-state nanopores in microfludic networks.	Optical fluorescence technologies.
Cellular Biometrology	Drug discovery and approval, determination of cytotoxicity of drugs and toxins.	Ability to control the cellular microenvironment; new electronic sensors; integration of electronics with microfluidics technology.	Robotic-based technologies, optical-based measurement technologies, RNA chips, polymerase chain reaction (PCR), others.
Information Processing	Bio-inspired computing	Methods to extract information stored on DNA.	Semiconductor electronics.

Molecular Electronics

The molecule is the single smallest thing that may ever have completely engineered electronic and optical properties. Therefore, molecular-based electronics, which can be viewed as the ultimate possible miniaturization, is a field that many predict will have important technological impacts on the computational and communication systems of the future. The goal for molecular electronics is to supplement or replace conventional Si-based technologies to extend electronic device performance improvements beyond the incremental scaling of Complementary Metal Oxide Semiconductor (CMOS) devices.

The small size of molecules is the source of their great promise for electronic scaling and functionalization. However, making reliable, reproducible electrical contacts to sub-lithographic nanoelectronic materials, such as molecules, is a great challenge. Test structures that typically contain ensembles of molecules and characterization techniques are required that enable the intrinsic properties of the molecules to be determined. These measurement methods must separate contact effects and test platform artifacts from the intrinsic molecular conductivity. Physical characterization of the molecules within a molecular electronic device (another metrology challenge) is critical to verify that observed electrical behavior is arising from a change in the molecules in the device. In addition, three-dimensional electromagnetic models incorporating quantum mechanical effects in the device materials are needed to fully understand and interpret measurements of molecular electronic behavior.

While the chemistry of self assembly enables contact to one side of a properly designed molecule to be well-controlled and relatively easily formed, making good electrical contact to the other side of molecule is the greatest challenge (and the greatest road-block) to the implementation of a molecular-based electronic technology. This challenge is amplified for single-molecule measurements.

In spite of these challenges, molecular electronics holds great promise as a technology to improve the performance of information processing technologies beyond the capabilities of the CMOS FET (Field Effect Transistor), the current basis of ULSI (Ultra-Large-Scale Integration) circuits, which is beginning to show fundamental limits associated with the laws of quantum mechanics and the limitations of fabrication techniques.

Application Area	Examples	Key Requirements	Competing Technologies
Applied Metrology	Self-assembled dielectric film thickness standards	Repeatable self assembly to form uniform, high-density molecular monolayers.	Atomic layer deposition (ALD), thermal oxidation.
Novel Measurements	Single molecule measurements	Electrical contact to single, isolated molecules. Separation of contact effects from intrinsic behavior.	None.
Novel Measurements	Intrinsic molecular effects	Reliable molecular electronic test structures. Correlation of physical properties with final device performance.	None.

Information Processing	Molecular electronic switches for advanced logic and memory	Electrically active molecules. Uniform, ultra-dense device fabrication. Reliable, long-term performance.	Si-CMOS, other proposed “beyond CMOS” technologies such as spintronics or phase-based circuitry.

Nanoscale microwave metrology and spintronics

There is a need to develop fundamental measurement techniques to allow the continued temporal and spatial scaling of present electronic devices, and to facilitate the development of emergent high-speed nanoelectronic device architectures. Present scaling laws predict that within the next decade the critical dimensions of charge- and spin-based electronic devices will approach only a few tens of nanometers and will operate at gigahertz frequencies. Few measurements have been performed in this regime. Furthermore, below 5 nm dimensions, CMOS devices are not expected to function reliably, and alternative device architectures, such as nanotube FETs and spintronic devices, are being explored as potential replacements.

While significant progress has been made in gaining a rudimentary understanding of these devices, it has largely been confined to low-frequency and dc operation. Presently, there is a lack of understanding of how such systems behave and couple to one another at frequencies from 100 MHz to above 100 GHz. In order for their potential to be realized, measurements methods in the gigahertz regime must be developed and understood. Such measurements are a “big” problem because: (1) the standard measurement techniques implemented at low frequencies cannot be applied or extrapolated to the microwave regime; (2) combining high spatial resolution with high frequency and/or broad bandwidth is very difficult; (3) the high impedances characteristic of nanoscale devices are very poorly matched to existing, almost exclusively 50 ohm, reference instrumentation; (4) metrologies must be capable of characterizing single defects since they can affect or even dominate device behavior; (5) environmental and probe-device interactions can strongly influence nanoscale devices and lead to unexpected behaviors; and (6) at nanoscale sizes devices can dynamically interact with the electrons flowing through them so that the measurement itself can affect the device response.

The need of the electronics and data storage industries for characterization of nanoscale high speed devices with metrological accuracy is driven by their aggressive push for nanometer/molecular scale devices operating at frequencies approaching 100 GHz. This demands a new physical understanding of electromagnetic properties of nanoscale objects *at high frequencies and in the near field regime*. Electrical methods, such as noise- or resonance-based metrologies, need to be developed to characterize the role of defects in realistic and active device structures. Metrological methods need to be developed to (1) identify the dynamic response of both spintronic and conventional electronic devices to current carrying electrons on the sub-nanosecond time-scale and (2) characterize the interaction of devices with their environment.

Advances in nanoscale microwave metrology will have impact on a wide variety of applications. These include high speed molecular electronics, high density storage, semiconductor-based integrated circuits, spintronic devices, quantum computing, and other alternative computing architectures proposed beyond CMOS. An example is the impedance matching problem in high density circuits. This requires strict tolerances on individual device impedances in order to efficiently integrate nanoscale FET-based devices together; the problem becomes increasingly difficult as characteristic dimensions shrink. The table below provides additional information on application areas and requirements for improvements in nanoscale microwave metrology.

Application Area	Examples	Key Requirements	Competing Technologies
Applied Metrology	Calibrated S-parameter measurements at arbitrary reference impedance. This includes clarification of the meaning of equivalent complex wave amplitudes and phases, impedances in nano-structures at microwave/millimeter wave frequencies with critical evaluation of their definitions.	Accuracy and traceability, impedance compatibility	None, at present, though some development is pursued in industrial laboratories. All the existing approaches are 50 ohm reference impedance based.
Applied Metrology	Time and frequency domain metrology for micro/millimeter wave nanoelectronics.	Sensitivity, accuracy, spatial resolution, and traceability.	None, at present. This type of metrology is partly developed in optics, but does not exist at microwave frequencies.
Novel Measurements	Near field chemical-sensitive specific spectroscopy such as near field EPR or NMR and nanoscale material characterization. High resolution spectroscopy of magnetic nanostructures, characterization of charge-based single-photon sources, particle detectors, electromagnetic field mapping, etc. Device control with electron spin.	Combined spatial resolution, bandwidth and chemical sensitivity.	More expensive and elaborate time resolved synchrotron and x-ray approaches

Information Processing	Active spintronic devices, nanoscale microwave sources and spectral analysis, magnetic random access memory, hard disk drives.	Improvements upon CMOS, microwave power output, ultra-high speed behavior, nanoscale spectroscopy.	Quantum computing, MEMS/NEMS, optical processing.

Nanomagnetism

Nanomagnetic structures and devices are penetrating various sectors of today´s society ranging from information and communication technology to health care. While a sound metrological basis including standards and traceability chains has been established for measuring the magnetic properties of macroscopic objects, metrology for nanomagnetism is still in its infancy. Outlined below are “big problems” of nanomagnetism, among them some that are common to nanotechnology in general (e.g., refer to the section above on nanoscale microwave metrology).

While traceable measurement techniques for the magnetic field and the magnetization have limited spatial resolution, high-resolution microscopy techniques are lacking traceability (e.g., Lorentz microscopy, magnetic force microscopy, spin polarized scanning tunneling microscopy). Thus, efforts are required to trace back nanoscale measurements to the existing macroscopic standards. Along with this effort, the sensitivity and spatial resolution of magnetic field probes like nano-SQUID and nano-Hall sensors need to be increased. In some cases, the invasiveness of the measurements process, i.e., the change of the measured object in response to the probe, has also to be addressed.

Nanomagnetic structures often exhibit ultrafast dynamic behavior with bandwidths in the GHz range and beyond. The large bandwidth is inherently linked to their small size, e.g., GHz precessional dynamics is based on a macrospin approximation, which is only valid for single-domain structures. Traceable methods for the measurement of ultrafast magnetization switching need to be developed along with standards for high-frequency test beds for ultrafast measurements (coplanar waveguides, microstrip lines).

Research in nanomagnetism has led to the discovery of qualitatively new device concepts and devices such as, e.g., spin-torque memory cells and spin-torque oscillators, for which metrology is required. This development together with the effort to merge magnetism with semiconductor technology in the field of semiconductor spintronics has drawn the attention to physical quantities that were less important in magnetic metrology in the past. This includes, e.g., the degree of spin polarization of spin polarized currents or the efficiency of spin injection over an interface between different materials. Providing a sound metrological basis for the measurement of these quantities presents a considerable challenge.

Meeting the challenges outlined above will impact key information and communication technologies like high-density data storage or non-volatile computers memories. In medicine and life science solving the big problems of nanomagnetic metrology will bring substantial benefits to all technologies that rely on magnetic nanoparticles.

SI Traceable High-Frequency Electromagnetic Field Measurements

Ideally, radio-frequency (audio to optical) electromagnetic field measurements (electric field in V/m and magnetic field in A/m) would be directly linked to SI units with low intrusion, fast response, wide dynamic range (mV/m to kV/m and μA/m to A/m) and low uncertainty (less than 0.1 dB or less than 1%). The current state-of-the art is far short of this goal. At present, radio-frequency electromagnetic field measurements typically assume far-field conditions, measure the electric field only, use a small dipole with a diode based voltage detector, are only indirectly linked to the SI units, cannot accurately detect fields below 1 V/m, and have uncertainties on the order of 0.5 dB or greater than 5%. Presently used electromagnetic field probes were developed some 20 years ago and could be improved based on advances in materials and electronics. However, to achieve an order of magnitude improvement (or several orders) a new physical approach to electromagnetic field measurements is needed. No NMI has been able to improve on the diode probes to date. A true breakthrough improvement remains a difficult EM problem.

Optical modulators are a low intrusion alternative to dipoles; however, they cannot currently achieve significant sensitivity or accuracy gains. Electromagnetic field probes based on Rabi oscillations could potentially achieve high sensitivity and low uncertainty, but no obvious way to go from this atomic scale effect to a usable field probe presently exists. The Stark effect couples field strength with line spectra of a gas and may present a possible approach; however, again it is not clear how to go from this quantum effect to a usable field probe.

Development of a more robust foundation for electromagnetic field measurements is extremely unlikely except with the focused attention of the NMI community. Improved electromagnetic field probes would improve traceability worldwide and would also benefit high performance electromagnetic systems, such as radar, satellite, radiometer, and communication systems. Higher sensitivity and higher accuracy sensors and instrumentation would also enable new applications in electromagnetic imaging, in particular biomedical applications.

Quantized resistances of QHR arrays, newly fabricated materials, and related CCC technique.

Since 1990, a single bar QHR (Quantized Hall Resistance) is adopted as a primary standard of DC resistance. Quantized Hall Array Resistance Standards (QHARS) have been studied extensively and in the future they could be working standards if the technique for the fabrication process of the arrays is finalized. And hopefully QHARS could be recognized as a primary standard after sufficient evaluation. Crystal growth of GaAs/AlGaAs heterostructures has been well developed, high quality substrates are utilized for many applications. The newest techniques of fabrication of high quality ohmic contacts and insulation layers could be applied to the integration of QHR bars. High quality substrates could reduce the required magnetic fields. Arrays of value 100 Ω or 10 kΩ could be very useful for traveling standards first of all, and as working standards in many NMIs.

Recently various new heterostructure materials have been fabricated with the state-of-the-art combinatorial method, and surveyed for various purposes and in some cases in quest of a high-mobility electron gas. For example, in $ZnO/Mg_xZn_{1-x}O$ heterostructures Shubnikov-de Haas oscillation and quantized Hall resistance were reported. And a $LaAlO_3/SrTiO_3$ heterostructure was confirmed to have very high mobility and showed Shubnikov-de Haas oscillation. It is important to monitor the material fabrication research in that field, and, if necessary, we have to evaluate such materials from the metrology point of view.

In March 2007, graphene (single layer graphite) was reported to show quantized Hall resistance at 300 K. Electrically or chemically doped carriers of graphene have sub-micrometer-scale ballistic transport properties. And it also acts as weak link between superconducting electrodes and demonstrates the Josephson effect. It is reported that nanometer ribbons and quantum dot structures carved in graphene have a SET-like behavior. This incredible material could be a candidate to replace current GaAs/AlGaAs heterostructure-based QHR standard devices. Because its Landau levels split largely with several hundred to several thousand kelvins, we might have a possibility to operate the QHR at an elevated temperature and/or at lower magnetic field. The universality of the quantum Hall effect of graphene in comparison with that of a GaAs/AlGaAs heterostructure has been confirmed recently. If in addition to this the operation in moderate conditions will become possible after enough evaluation, a QHR system might be utilized at various laboratories, not only at expert NMIs.

It is believed that the electronics of CCC is well matured. But CCC cores are still handcrafted. If it would be possible to fabricate such CCC cores in a superconducting process, as it is widely utilized in Josephson junction fabrication technique (i.e. Nb-Al process), CCCs could then be cooled by compact liquid helium-free cryostats. In this case, CCC bridges could be utilized in many NMIs and replace conventional DCCs in some cases. For this purpose, the thickness and quality of the Nb and insulation layers are important.

Traceable THz Metrology

Terahertz (THz) technology is a rapidly growing field with a wide range of exciting early applications that take advantage of unique material properties at these frequencies. Applications include medical imaging systems, spectroscopy of molecular and biological systems, remote sensing and standoff detection for homeland security, atmospheric monitoring for pollutants and climate change science and cosmic microwave background

(CMB) measurement to research the origin of the Universe and the physical laws governing the Universe. All of these efforts are for the development of components or measurement systems aimed at specific applications, with no concerted effort to address the underlying metrology infrastructure. NMIs will be needed to develop and deliver the essential measurement techniques and standards required to provide reliable and robust traceability for key measurement parameters in the terahertz frequency range. At present the THz community attempts to meet its metrology needs in an ad hoc fashion, generally using microwave or IR components far beyond their specified frequency range, even though basic physics considerations suggest they would be inaccurate. Microwave measurements currently reach up to ~100 GHz, while IR techniques extend to below ~10 THz. For the THz frequencies in between, this has left even the most basic of metrological tools, such as power meters, with serious gaps in capabilities over the needed power and frequency ranges, and without traceability. Immediate critical needs of the THz community are calibrated power measurements and the instrumentation and techniques to make quantifiable THz measurements of material properties and the interactions between THz radiation and measurement systems. As for CMB measurement it is believed since recently that the information of CMB polarization, which is measured by superconducting detectors, will play an important role to disclose the true figure of the Universe in the time shortly before the Big Bang. Quick and accurate calibration technique for such detectors will contribute to this scientific activity.

High-speed Communications and associated metrology

The NMIs must continue to develop next generation measurement methods and services for high-speed waveform measurements and other metrologies to support advanced high-speed communications. Such measurements include traceable measurements of ultra-fast pulses, combining time and frequency domain techniques, as well as new systems level measurements for both optical and wireless. For example, to economically meet growing demand for capacity, networks must optimize use of infrastructure and spectrum. This requires more efficient use of bandwidth and extensive reconfigurability of network elements, including routing of paths and channels. These advances require development of completely new paradigms to support physical layer measurements for both fiber optic and wireless systems. The measurement needs for next-generation networks far exceed today’s capabilities and demand a multidisciplinary approach that accurately quantifies the physical-layer performance of frequency-, waveform-, and path-agile networks.

Physiological effects of ac and dc magnetic fields

The highest magnetic fields to which the human body is normally exposed occur during magnetic resonance imaging (MRI). Clinical MRI systems create static magnetic flux densities of typically 1.5 to 3 T and smaller superimposed radio frequency (RF) fields.

Regulations exist or are in preparation to limit the exposure to the risks arising from electromagnetic fields. These risks include effects on nervous system functions in the body, and the recent EU Directive 2004/40/EC defines exposure limits for workers in the frequency range from 1 Hz to 10 MHz with respect to the induced maximum current densities in the human body. The link between these induced current densities and the related, more directly accessible electric and magnetic field strengths is based on numerical modelling, but no experimental verification exists. Also, the knowledge of physiological reference data, as for example tissue conductivities in the human body, is very limited. Motion of workers in the stray field of MRI scanners or other large dc magnets also leads to induced currents, which can become significantly large. At present, these current densities are determined by numerical modelling but also in this case no experimental verification exists.

A possible field of contribution of metrology would be the measurement of physiological properties needed as input for the calculations. It might also be useful that the CCEM or NMIs active in this field establish contact with ICNIRP, the International Commission on Non-Ionizing Radiation Protection, which is recognized by the WHO, ILO and other bodies as the international independent advisory body for this field.

Other specific technical metrology challenges

Communication with nanosystems (acoustical, optical, electromagnetic, nano-micro interface)

Nanomeasurements (CNT properties)

Fermi surface measurement

Societal, Economic, and Cross-cutting Areas

Energy
    Smart Grid (intelligent electric grid)
    Transformer and other power equipment efficiency
    Fuel cell
    Solar
Environment
    Climate change
    Detectors for monitoring
Health
    Bioelectronic (mentioned above)
    Toxicity ??
    Electronic Implants
    Imaging
    EMF effects (cellular telephones)

Homeland Security

Challenges facing the NMIs and RMOs

Interactions with national SDOs, international standards bodies, and accreditation bodies.

Efficiently and effectively supporting the CIPM MRA with a well-designed key comparison process using stable and appropriate transfer.

Mutual agreement among regional NMIs which would enable the termination of some services offered elsewhere in the region.