# European Metrology Research Programme

# Outline 2008

*Edition - November 2008*

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"*This document outlines the European metrology research programme and consists of an extended Executive Summary which can be read as a stand-alone document, followed by a more detailed description of the context and joint research programme. It outlines the processes that will be implemented under Article 169 and, for completeness, other EURAMET relevant activities including the pilot phase implemented under "ERA-NET Plus" and Metrology Knowledge transfer, including education and training.*

# I EXECUTIVE SUMMARY

**With the overall goal of accelerating innovation and competitiveness, generating data and knowledge necessary to improve quality of life, and providing better tools for the scientific community the European Metrology Research Programme aims, through European integration, to develop new measurement capabilities which have strategic impact for Europe.**

*"Measurement, testing and the definition of common standards, are essential elements in the establishment of a knowledge-based economy that the European Union is striving to build. In this context, a powerful European metrology infrastructure is crucial to ensure the proper functioning of the European single market and to strengthen the competitive position of European enterprises in the global marketplace."*[1]

Modern society requires reliable measurements that give the same answer wherever they are made. This is achieved by ensuring traceability to the International System of Units referred to as the SI, covering the base units (metre, kilogram, second, kelvin, candela, ampere, mole) and the derived units. This system is based on and, in turn, supports continual and long-term research in fundamental science and technology. In the modern world, comparability of measurements and interoperability is crucial, with an obvious example being the atomic clocks that form the basis of international time keeping, and with it communications, banking, navigation etc. Quality-assured measurement, with traceability to international standards and with quoted uncertainty, provides an objective base for decision-making in the conformity assessment of products and processes of all kinds; thus enabling international trade, manufacturing, communication as well as ensuring health, safety, security and protection of the environment.

Increased needs of society for traceable measurement, in traditional sectors (manufacturing, communication, food, environment etc) as well as new areas (such as nanotechnology and biotechnology) become increasingly resource intensive. This is a challenge best met by increased cooperation. The **context** of the European Metrology Research Programme (EMRP) is to enable Europe to respond in an integrated way to the growing demands for cutting-edge metrology as a tool for innovation, scientific research and support for policy, particularly in emerging technological areas.

The **programme objective** is to accelerate the development of new measurement capabilities and to improve significantly the dissemination and application of knowledge generated throughout the stakeholder community.

The Joint Programme is based on Article 169 of the European treaty. The European Commission (EC) will co-fund this Joint Programme through Article 169 - the most advanced instrument for the integration of European Research. The EMRP will play an important part in the construction of the wider European Research Area. The **budget** of the EMRP is

[1] Philippe Busquin, EC Commissioner for Research, Conference, "*An Integrated Infrastructure for Measurement*", Warsaw 2002

approximately 400 M€ for a seven year period.. The European Metrology Research Programme (EMRP) is implemented by the organisation EURAMET[2] which is the European Association of National Metrology Institutes. The EMRP is a partnership between 19 EU Member states[3], 2 EFTA countries[4] and Turkey. It aims to integrate relevant European national programmes and activities to accelerate the development of vital research capabilities that, on the one hand supports competitiveness and on the other hand provides an infrastructure that supports EU policies.

The activities of the EMRP include five main topics:

1. Activities linked to networking and coordination of the national research and development programmes and activities for measurement that continue to be conducted at a national level outside of the core EMRP joint programme, particularly:
    a. Investments in new national measurement research facilities;
    b. Opening of existing national measurement research facilities;
    c. Opening of the national measurement training and knowledge transfer programmes supporting research and technological development.
2. Activities related to the joint programme as delivered by the National Metrology Institutes, and the institutes designated by them, namely research and innovation in measurement science:
    a. Supporting innovation;
    b. Supporting quality of life and European policy;
    c. Supporting the wider scientific community.
3. Additionally:
    a. Research and technological development in fundamental and underpinning measurement science;
    b. Knowledge transfer activities to support the research and innovation.
4. Capacity building activities embracing excellence in science, principally through three grant schemes aimed at the wider community of European National Metrology Institute laboratories and the science community beyond the NMIs, augmented by activities promoting participation in knowledge transfer and training activities, including access for those members of EURAMET from States who are not participants in the Article 169. Knowledge transfer activities in a *two-way* information exchange between national metrology institutes and metrology stakeholders (universities, practitioners, industry, government, regulators etc) to support research and innovation.
5. Activities related to the visibility, governance and management of the joint programme such as:

    a. Visibility and promotion of the programme to stakeholders;
    b. Governance, advice, steering and stakeholder input;
    c. Sustainability, ensuring appropriate evolution of the programme including beyond the period covered by the Decision;
    d. Secretariat services, including operation of project selection processes and procedures, management of information and all support services;
    e. Reporting on the implementation of the joint programme.

[2] EURAMET European Association of National Metrology Institutes www.euramet.eu
[3] Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, The Netherlands, Poland, Portugal, Republic of Slovakia, Romania, Slovenia, Spain, Sweden, United Kingdom
[4] Norway, Switzerland

The **national metrology research programmes** are defined as publicly funded research activities related to the National Measurement Systems within individual countries participating in and contributing to the EMRP.

Practically all governments in advanced technological countries support a measurement infrastructure because of the benefits it brings; to drive innovation, to support sound policy and regulation (and thus to protect us, the citizen) and to provide ever better tools for other scientific disciplines. The measurement infrastructure and the associated research are managed and delivered via National Metrology Institutes (NMIs) and Designated Institutes (DIs)[5]. The NMIs are additionally charged with ensuring the international system of measurement, the SI, functions appropriately. These, as any research institutes, have a mediating role between the academic and industrial sectors in transferring metrological knowledge.

The application of Article 169 implies the national commitment of each participating State to mobilise their publicly funded organisations active in the field of the EMRP, and to commit a part of their national resources to Europe during the life of the Joint Programme.

The **Governance of the EMRP** is assured by executing the Joint Programme through a common structure, a non-profit association according to German civil law (eingetragener Verein, e.V. §§ 21 – 79 German Civil Code (BGB)), with the legal title of EURAMET e.V., hereafter referred to as EURAMET. This legal entity has a scope which includes not only the execution of the EMRP but also tasks and obligations related to the wider European and global harmonisation of metrology. Consequently, membership of EURAMET e.V. is in principle open to all European countries through their national metrology institutes. EMRP partners form the substructure of the wider EURAMET e.V. for all matters of the EMRP.

EURAMET is charged with implementing the EMRP, will develop and execute the EMRP joint programme and provides the legal, financial and operational structures needed to receive, dispense and account for funds and manage the activities. The e.V. is composed of 8 main bodies:

- The “General Assembly” of the members of the e.V, the highest authority within the association. It will decide on all matters of the wider EURAMET, however on issues related to the execution of the EMRP the General Assembly will act on the binding recommendation of the EMRP Committee.
- The “EMRP Chair”, who will represents EURAMET e.V. in matters of the EMRP.
- The e.V. “Board”, which will be responsible for ensuring the implementation of the decisions of the General Assembly and will determine the measures necessary to fulfil the EURAMET aims.
- The e.V “Secretariat”, which will provide administrative support for the work of EURAMET including a dedicated EMRP Management unit to aid in the implementation and the execution of the EMRP. It will support the work of the General Assembly, the Board, the EMRP Committee and the Research Council.
- The “EMRP Committee” which is the decision body responsible for all aspects related to the EMRP Joint Programme, including: the programme content, funding issues, deciding on capacity building measures, calls for proposals, evaluation criteria, identification of experts to evaluate proposals and the final selection decision for proposals. The EMRP Committee includes representation from the Article 169 participating States only.
- The “EMRP Committee Chair”, who represents EURAMET e.V. in the matters of the EMRP.

[5] National Metrology Institutes (NMIs) and designated Institutes (DIs) will be mentioned collectively as NMIs in the text.

- The “Research Council”, which will give strategic advice to the EMRP Committee on EMRP matters. The Council will include a balanced contingent of stakeholders principally from the participating States, including for example institutional and industrial key interest groups drawn from bodies such as the BIPM, the European Commission, the European Research Council, the European Parliament, EUROLAB, CEN, WELMEC augmented by personal members appointed for their strategic expertise.
- The “EMRP Programme Manager” manages the EMRP management unit, acts solely under the direct authority of EURAMET e.V. and reports to the EMRP chair.

The national resources contributed to the **budget** of the Joint Programme are estimated at 200 M€ over the nominal 7-year period of the EMRP. Furthermore each country will maintain a defined reserve budget to ensure that the selection of projects, which is based on excellence and relevance, is not compromised by budget limitations in any one participating country. The total of the reserve is estimated at 100 M€. The European Commission will contribute the sum of 200 M€ to increase the impact of the EMRP. Alongside the main NMI research project activity, researchers from outside can participate with the European NMIs in the identification of research topics and in applying for researcher grants (including mobility) which make up 10% of the EMRP[6].

Operational management costs are limited to 4 % of the total programme value and are covered by direct contributions from those member countries of the e.V. participating in the Article 169. Costs associated with operation of the e.V. Secretariat which are not related to the joint research programme will be met separately by all EURAMET e.V. members.

The **EMRP work programme** will adopt a two-axis approach to the research, addressing on the one hand “grand challenges” and on the other “applied and fundamental metrology”. In addition, a grant system is available for capacity building in European countries which have little or no metrology R&D capability so far, and for researchers from capable European research organizations irrespective of their responsibility for the national metrology systems.

**Theme I** of the EMRP, the largest theme in budgetary terms, will bring the collective research capabilities of the European NMIs to bear in a completely new “top down” approach. By corralling and focusing expertise and R&D resources across the metrology disciplines on identified measurement and metrology needs for the “Grand Challenges” of European and international relevance – for example environment and climate change, energy supply, health and security – significantly greater impact will be achieved.
**Theme II,** the “applied and fundamental metrology” activity area, will encompass the top down multidisciplinary metrology R&D necessary to produce the step change advances within the international system of units, and the bottom up focussed research challenges in specific technical fields with strong input from the well-established technical committees.

Based on the experience so far gained in the framework of ERANET plus, which has been implemented as a bridging measure towards a programme execution under Article 169, a Rolling Plan has been established to implement the programme under Article 169. The Rolling Plan and associated budgets will be updated and specified annually.

[6] Eligibility for researcher grants is given in § *III.3.13*

## I.1 Activity areas

Metrology is a horizontal scientific-technical field which underpins almost all subject fields in natural sciences and engineering. It is a technically wide and multidisciplinary field under a common methodology – characterized by the scientific treatment of measurement uncertainties, mathematical methods and principles of metrological traceability. Metrology is internationally structured under the intergovernmental Metre Convention and its organisations such as the International Committee for Weights and Measures (*CIPM - Comité international des poids et mesures).* The EMRP addresses metrological research activities at the frontiers of measurement science in order to meet the most urgent industrial and societal needs.

Metrological research and development is usually addressed in a single-discipline approach along a scheme of technical fields given by the Consultative Committees of the CIPM and the Technical Committees of EURAMET. This approach is powerful in many cases, especially in the established fields, and will be part of the EMRP. An increasing number of challenges, however, require a more multidisciplinary approach due to the complexity of the topics. Thus coordination within the EMRP does not only mean coordination of national programmes in a specific field but also coordination of different research activities driven by a complex challenge.

Consequently, the activity areas of the EMRP are structured in

- Grand challenges for multidiscipline metrology (*health, energy, environment, new technologies*).
- Grand challenges on fundamental metrology.
- Focussed single-discipline and applied metrology.

All metrological research itself is supported by a common mathematics and software programme.

### *I.1.1 Grand challenges*

**Grand challenges** comprise multidisciplinary metrology research needed to meet key socio economic objectives in the fields **health, energy, environment, and new technologies**. These fields require a research approach that – driven by the challenge – combines various technologies and methods. However, metrology research in Europe in these fields has so far been rather fragmented and not yet been strategically coordinated. In the EMRP, existing research activities and capabilities, which are directly related to the above-mentioned fields and which require a multidisciplinary approach, are combined, coordinated and supplemented by missing research needs.

The priority setting will be carried out in consultation with the Research Council representing the key stakeholders. The selection of fields reflects the character of metrology as a horizontal research field with particular underpinning relevance for the 7$^{th}$ framework programme.

***Health***

Metrology for health underpins the more reliable and efficient exploitation of diagnostic and therapeutic methods and the development of new techniques, which is needed to improve health care, limit costs and foster the competitiveness of the related European industries and services. In addition, legislation requires more and more substances and techniques to be covered by metrology such as through the EU medical devices and in-vitro diagnostic directives.

In the framework of the EMRP, the most competitive metrological activities within the national research programmes, which are directly related to health applications, have been collated and supplemented by new topics to form a coherent and comprehensive approach on metrology for health.
The programme includes :

- The expansion of the range of “reference measurement procedures and reference materials of a higher order” as recommended by the International Joint Committee for Traceability in Laboratory Medicine (JCTLM), a joint body of CIPM, the International Federation of Clinical Chemistry and laboratory medicine (IFCC) and the International Laboratory Accreditation Co-operation (ILAC).
- The “virtual human”, which refers to a model of the human anatomy and the human functions as a comprehensive reference standard for manufacturers of medical instrumentation, medical R&D, modelling and training.
- Quantitative instead of only qualitative diagnostics including imaging, modern microscopy and traceable multimodal measurement procedures.
- Diagnostical and therapeutical instrumentation including the use of electrical and magnetic biosignals, fluorescence optics, validated biomarkers, nuclear magnetic resonance (NMR) and ultrasound; instrumentation involving ionising radiation is described in chapter I.1.2.

***Energy***

One of the current challenges is to explore the different solutions for transforming the current fossil fuel energy system into more sustainable ones based on a wide range of renewable energy sources. This challenge for new sources of energy addresses new technologies as well as energy efficiency, security of supply, climate change (highly connected with environment and climate changes) and EU competitiveness.
On the one hand, the current energy systems such as thermal, electrical or nuclear must have their efficiency improved to save the currently used basic sources such as fossilized energy or radioactive material. Needs include improved measuring devices for the quality of the electricity, combustion of fuel or temperature control in power plants.
On the other hand, research is strongly needed for the development of the new renewable energy sources in terms of characterisation and comparison of their efficiency as well as the knowledge of how they are used by the consumer or the end user. The sustainability of the energy sources is addressed in that sense. The programme includes necessary metrology support to:

- toughen up conventional energy systems;
- develop new and renewable energy sources (hydrogen and fuel cell technology, wind, biomass, nuclear fission, solar-powered energy systems, etc..);
- increase in efficiency, flexibility safety and reliability of current energy networks (smart energy networks);
- improve energy efficiency and savings.

***Environment***

A key challenge facing the EU is the need to ensure continuous and sustainable growth whilst reducing negative environmental impacts. Many of the activities required to achieve this will depend on new stable and comparable measurement standards for environmental changes and the environmental performance of new technologies. These typically involve measurements at much lower levels and over longer timescales than are required to address other themes within the EMRP. The nature of the challenges faced in protecting the environment and in developing new sustainable technologies dictates a multi-disciplinary approach that will drive the requirement for research within the EMRP that brings together different disciplines within measurement science. The activities to be addressed most urgently through research include validated and traceable measurement techniques, sensors and measurement standards related to:

- detecting change and monitoring climate;
- measuring flow and concentration of species under regulation such as the Kyoto protocol;
- efficient and sustainable use of resources;
- longer-term carbon dioxide sequestration ;
- assessment and management of environmental noise.

Such validations of traceable measurements technique will also have the address the specific technological challenge of conducting such measurements of environmental parameters from spaced-based platforms, where both measurements accuracy and long-term stability of measurement instrumentation pose specific challenges.

***New Technologies***

Nanotechnology is a key enabling technology. The driving forces behind are the demand for ever increasing integration, e.g. in electronics and information technology, as well as the possibility of achieving new functionalities which are not possible otherwise such as through nano-structured surfaces, photonic crystals, optical meta-materials, and nano-particles. In many cases in nanotechnology, quantum-mechanical effects prohibit a scaling-down of properties of micro systems and thus require new scientific approaches. In the EMRP, the following metrological key challenges have been identified:

- development and combined application of optical and scanning probe microscopy for analysis of nano-structured surfaces, nano-particles and photo masks for semiconductor manufacturing;
- nano-electronics, nano-magnetic and nano-electro-mechanical systems: research towards measurement of sub-nm length, spatially resolved temperature profile of nano-circuits, electro-magnetical properties;
- nano-materials: research towards traceablity of toxicity measurements, shape, size, size distribution, chemical characterisation of nano-particles such as nano-tubes or combustion products.

Metrology is central to the development of instrumentation at the technological frontiers to meet the growing public **security** needs. Security-related metrology in the EMRP includes development and characterization of Terahertz (THz) sources and detectors for security applications, medical imaging, biological screening, e.g. of toxins in the atmosphere, and biological and pharmaceutical spectrometry of solids/liquids, neutron sources and detectors and novel chemical methods for the detection of hazardous materials. Another research option is underpinning quantum cryptography by entangled photon-sources which are also of interest in radiometry, and by validation procedures for information integrity, which also affects legal metrology.

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### *I.1.2 Metrology R&D for applied and fundamental metrology*

Metrology R&D for applied and fundamental metrology recognises the need to address both metrology R&D issues that require R&D effort across the traditional disciplines of metrology R&D, particularly addressing the call from the intergovernmental Metre Convention to focus research effort on the precise determination of the fundamental constants and a possible redefinition of the SI system, and focused R&D advancing the specific metrology disciplines and the individual quantities within the SI:

*I.1.2.1 Grand challenges of fundamental metrology*

Over the last decades, discoveries associated with new technologies, mainly in quantum physics, have led to important changes in thinking the world of metrology, in particular for fundamental metrology. The discoveries concern both the realisation of the base SI units and the possible redefinition of some units which could lead to an improved International System of Units (SI). The present trend is to connect directly current SI units to fundamental constants, different detailed proposals being in discussion. Irrespective of the preferred redefinition, the definitive choice must wait the consistent experimental results, and the SI system must keep its coherence and consistency. The two main axis are the followings :

- R and D that has the potential to result in a step change on the SI, taking into account CCs and CIPM recommendations (fundamental constants, major SI-redefinition projects with cross-disciplinary approaches.
- Multi discipline metrology R&D.

*I.1.2.2 Focussed single-discipline and applied metrology*

- Advanced realisations on base and derived SI units.
- Applied metrology to support innovation, products and services, including the necessary regulatory aspects.

**Ionising radiation**

The main objectives are concentrated on health and industrial applications. Advances in ionising radiation metrology immediately impacts on the quality of life through improved diagnostic and treatment of diseases like cancer.

Damage to nano-metric bio-systems like DNA and to new materials in nanotechnology needs a better understanding of interaction of ionising radiations with matter.

Development of novel types of radiation sources will be a basis for further optimising treatment methods provided they are backed by the necessary metrology.

The main activities to develop are:

- *Improvement of procedures and better knowledge of multidimensional dose distribution delivered both to patients and medical staff for radio-diagnostic and radiotherapy* .
- *New physical concepts and metrology for quantifying radiation interaction with matter.*
- *Realisation of new devices for the traceable characterisation of radiation sources.*

**Electricity and Magnetism**

Electrical measurements have a great impact on nearly all areas of research and development, industrial activities and quality of life. Non-electric measuring quantities are converted into electric quantities already at the sensor level and as such are transformed, processed, stored and transmitted. Therefore, electrical metrology plays a key role and underpins further development in FP 7 fields like health, ICT, nanotechnology, energy, environment, traffic and security. The following targets were identified:

- *Development of enhanced measuring capabilities for the assessment of the quality and efficiency of electrical power*, and for the monitoring and protection of power grids and apparatus.
- *Establishment of traceable specific radio frequency absorption rate dosimetry and EM field-strength measurements* at all frequencies that are in wide public use. This metrological basis is needed to address health and safety issues in connection with the pervasive use of broadcasting devices, particularly for mobile applications.

- *Extension of measurement methods and standards into the terahertz frequency range* underpinning the further advances in information and communication technologies as well as health and security issues.
- *Development of ultra-sensitive measurement tools allowing the characterisation of nanostructured materials*, components, devices and systems used in tomorrows nanoelectronics and nanomagnetics technology.
- Development of accurate, intrinsically referenced electrical measurements by for instance transportable electrical quantum standards serving the need of emerging technologies.

**Time and frequency**

The unit of time is considered as the most fundamental base unit. Almost all technological processes require precise timing or reference frequencies, respectively. Other units such as length are directly linked to the unit of time. In addition, time and frequency are the quantities which can be measured most precisely.

Advantages in the realisation and dissemination of time and frequency are expected to have wide-spread impact on innovation, science and daily life, e.g. GPS.

Europe NMIs provide enormous, however sometimes uncoordinated and fragmented, capabilities in atomic clocks, time scale generation, time dissemination, space technology, and network synchronization. Three research focuses have been identified that will capitalise on the existing potential to the full extent only in a European effort:

- *Development of novel atomic clocks with unprecedented accuracy:* frequency standards in the optical regime have to be developed to overcome the limitations of today's best primary frequency standards based on laser cooled caesium atoms.
- *Establishment of novel ways for time and frequency transfer:* Atomic clocks with lower instabilities and higher accuracies put more stringent requirements on the performance of time and frequency transfer systems. The existing tools such as Two-Way Satellite Time and Frequency Transfer (TWSTFT) based on telecom satellites or techniques exploiting signals from global navigation satellite systems like GPS or Galileo need to be developed further. In parallel, new techniques shall be investigated, allowing a link of the major European timing laboratories by optical fibre.
- *Atomic clocks for specific space applications:* Deep space missions and satellite navigation impose the most challenging requirements on accuracy and reliability of clocks. The development of a satellite-borne atomic clock with $10^{-17}$ capability is a long term goal.

**Photometry and Radiometry**

Novel optical metrology in photometry and radiometry is required for the rapidly developing optical and lighting technologies and photonics – providing the basis of the present "Century of the Photon". These technologies explore novel light sources, new spectral ranges and complex geometries, they effect optical monitoring, remote sensing and more efficient lighting and thus underpin many other fields such as health, energy, environment, safety and production. The fields that need to be addressed most urgently are:

- *Novel optical radiometrical capabilities for industry, quality of life and environmental applications*. A better knowledge of innovative complex light sources, photo-biological effects, environmental parameters, or renewable energy will require developments on 3D metrology for optical light sources, on radiometry for monitoring environment, on efficiency of light-to-energy conversion for solar energy, and on the establishment of unified radiometry from THz to EUV range. Environmental application of radiometry incorporates also developments toward conducting such measurements from space-based platforms.

- *Quantum-photon based standards for optical radiation*. Communication technologies, high speed communication, quantum computing require characterisation and development of single photon sources, detectors, optical fibres and all-in fibre distribution.
- *Physical measurements of visual perception for product quality and security purposes*. Product quality requests a quantifying metrology on what was a subjective assessment of appearance.

**Thermometry**

Under the keyword of "thermometry" all subject areas are summarised which are related to measurement of temperature, thermo-physical properties, humidity and moisture and to characterisation of reference materials for those measurements.

Temperature is one of the most frequently measured physical quantities in science and industry. That implies that precise knowledge of temperature and related quantities is fundamentally important, for the development of new and more efficient production techniques saving energy and other resources and reducing waste, and for control of societal problems of environment, climate and security. Humidity is of similar importance as a critical parameter in various production processes and a key indicator in climate models. The main research and development in the field of thermometry and humidity are:

- *Fundamental thermometry*. Research into new fixed points (conventional and high temperature), the future definition of the Kelvin in terms of fundamental constants, future temperature scales and practical primary thermometry.
- *Temperature measurement devices*. Priorities had been identified for applications in safety, security, healthcare environment, high technologies and sustainable resources: rapid and low-cost sensor calibration, new types of temperature sensors, self validating sensors, thermal and THz imaging.
- *Characterisation of thermal properties of materials*. Improved determinations of thermal transport properties essential for improving energy utilisation (particularly, novel insulation types). *Ab-initio* calculations of "impossible" to measure thermal properties are needed to optimise thermal model of high energy use industrial processes and ultimately, when validated, to negate the need for costly measurement.
- *Humidity measurements*. Quantification of water vapour is critical for climate models, and determination of water vapour important in production processes.

**Mass and related mechanical quantities**

Mechanics, which comprises quantities like mass, force, torque, pressure, acoustics, vibration, ultrasound and flow is key tool for industry, research and society because of their wide range of applications in aerospace, off-shore industries, robotics, micro and nano-technologies, manufacturing or even to support diagnosis in medicine. In consequence reliable and traceable standards are needed as well as research for their improvement. Four main research routes have been identified:

- *Fundamental research in mechanics* for physics, bio-technologies and pharmacology, with contribution to the new realisations and definitions of SI units.
- *Innovative set-ups for new industrial and societal needs, including inspections, i.e. for security purposes* : realisation of new devices, sensors and standards in dynamic conditions (for aerospace, medicine, transport, etc.), pressure standards for ultra high vacuum (UHV) and extreme UHV conditions.
- *Advanced techniques for traceability of flow units*.
- *Specific metrological developments in acoustics, ultrasound and vibration issues*.

**Length**

Dimensional measurements play a crucial role in almost every aspects of modern life. From nm tolerances for sub-µm device features like in semiconductor production to sub-mm tolerances on large fuselage components: dimensional quantities are key parameters for manufacturing, process control and fundamental metrology and are of great importance in nanotechnology, ICT, transport, space and health area. Hence objectives to be addressed are:

- *Development of measurement techniques and sensors for the measurement in the micro- and nano-meter range*, supporting the increasing level of integration and miniaturization, the new issues nano-structured materials, novel bottom-up manufacturing processes as well as the investigation of the impact of nano-particles or nano-sized entities on human health;
- *Improvement of dimensional metrology for advanced manufacturing in well-controlled to harsh production environments*; allowing for a cost-effective, competitive and sustainable industrial production in Europe. European technology areas like e.g. automotive, machine tool or aerospace industries will benefit from development of traceable, fast and robust in-process metrology enabling improved process control;
- *Extension of dimensional measurement capabilities over large ranges up to several km* to support large scale production, satellite based navigation systems (Galileo) and long-term stability monitoring of sub-terrestrial cave systems used for waste management or storage of gaseous or liquid energy sources;
- *Development of new methods, instruments and modelling in length metrology enabling further progress in the research into fundamental constants and basic physics.*

**Metrology in Chemistry**

Metrology in chemistry is considered as one of the most rapidly growing fields of metrology, driven by the need for reliable chemical measurements in many fields of our daily life and requests from global trade and national as well as International/European legislation. Areas, which require new and harmonized measurement standards are, for example, .

clinical chemistry, food or environmental monitoring (see, e.g., 96/23/EC (residues in food), 96/62/EC (air quality control), 98/83/EC (drinking water), 2000/60/EC (water framework directive) or 98/79/EC (In vitro Diagnostic Medical Devices (IVD)-Directive) and many others).

Central aim for the NMIs therefore is to establish an international primary reference network for traceability in chemistry and electrochemistry. Urgent needs in important areas like food analysis, environmental monitoring are currently tacked by NMIs. Recently, the metrological approach has been remarkably successful in clinical chemistry. Others sectors, such as forensics have ot been addressed so far. The huge number of different analytes to be covered requires a distribution of tasks among the European laboratories, making this field especially well suited for a coordinated approach.

The central aim of EMRP is to underpin this European reference network through research and development of primary methods and measurement procedures, such as isotope-dilution mass spectrometry and surface-enhanced Raman spectroscopy, especially for large molecules such as proteins and biomarkers. Residues of veterinary drugs, pathogens, toxins and also GMOs are key targets in food analysis. In forensics, indicators of drug abuse, hazardous materials relevant for public security but also the quality of DNA-identification need to be addressed most urgently. Another topic that requires urgent metrological backing is the toxicity of nano-particles.

In addition, a particular metrological challenge is to provide reliability and comparability for new analytical technologies such as in-line and on-line measurements in industry, “lab-on-a-chip” devices, remote sensing instrumentation, high throughput screening devices, and new technologies such as surface-, micro- and nano-analytical measurement methods or single molecule counting.

## R&D for emerging metrology areas

### *Biotechnology*

Metrology is of increasing importance to the biotechnology community and is in increasing demand. The context is the need to create a sound international basis for accurate reliable and comparable measurements underpinning the development and exploitation of biotechnology by European industry. Thus the emerging field of bio-metrology is placing new and growing demands on the metrology research community which needs a co-ordinated European approach at this early stage to maximise potential. The specific requirements are to provide the metrology to ensure compliance with health and production related regulation, and to help Europe innovate through the development and validation of new and novel measurement methods. Reliable and valid measurement methods are key to driving increased production efficiency, product safety and improved therapy and diagnostics.

Bio-metrology is critical for three key areas: healthcare (prognosis, diagnosis and therapeutics), bio-production (bio-processing, bio-fuels and biodegradable products) and security (monitoring, remediation and food). Priority setting will take account of the need to underpin priorities as identified in FP7 and the spectrum of research will be aligned with related topics in the EMRP.

### *Metrology for New materials*

Materials developments are pervasive in our lives as the building blocks for everything around us contributing enormously to improvements in health, the environment and wealth creation through, for example, modern medical implants, cheap renewable energy from photovoltaic or major changes in telecommunications. Material science is undergoing a revolution, with new materials “designed for function” offering the potential to generate products and provide services that would be impossible with conventional materials. However such materials, in particular higher performance nano-materials, bio-materials meta-materials and hybrid materials bring particular metrological challenges due to their very nature, scale and special properties and the combination of two or more functions in a single material. It is important to be able to quantify the complex interplay of the microscopic state and the resultant properties. Major challenges exist in validating and understanding the inter-relationship of measurements in four areas: *Physical-chemical properties, Structural and compositional analysis, Constitutive properties of materials, Modelling of materials.* Establishing confidence in these materials measurements enables European Directives, certification and other regulative requirements to be met.

### *Mathematics and ICT for metrology*

Already today, hardware and software as well as mathematical methods are integral parts of almost all measurement procedures and many measurements rely on information communication technology (ICT) for data acquisition, analysis and display. The next generation of metrology systems will rely on further advances of mathematics and ICT.
It is necessary, e.g., to develop reliable mathematical models, to enhance the capabilities for data analysis, to ensure the trustworthiness of complex software and to incorporate arising communication technologies. This will result in intelligent, self-learning, self-calibrating and error-tolerant, adaptive distributed systems. It will also become increasingly important to develop mathematical approaches to obtain measurement uncertainty budgets and ensure

the integrity of the measurement processes for complex systems. Standard approaches fail to describe such systems and therefore more general concepts and guidelines are required to deal with these challenges. It is furthermore essential to enhance the trustworthy of software and measurement data by developing appropriate validation technologies and security concepts.

#### *I.1.3 Capacity building, KT and support activities*

Capacity building and future EMRP activities will address the two key axis, long term direction of the EMRP, including issues related to sustainability, and breadth through increased capacity for R&D and increased impact through knowledge transfer over and above that built into individual Targeted Programmes. The Theme addresses both the partner country NMIs and the wider world, specifically European NMIs that are not participating in the Article 169 and university researchers and industrial able to contribute significantly new ideas to the objectives of the joint programme.

##### *I.1.3.1 Capacity building*

**Researcher Grants**

Grants will be competitive and will target Emerging European NMIs wishing to initiate or increase capability in R&D and European researchers, typically University or Research laboratory researchers:

- Researcher excellence grants;
- Researcher mobility grants;
- Early-stage researcher mobility grants.

**Education & Training**

- Development of joint education and training material
- Access to national education and training material
- Other joint knowledge transfer activities relevant to the programme

**National links**

Improving links between national activities that continue to lie outside of the EMRP

- Participation in national programmes
- Special facilities

##### *I.1.3.2 EMRP future activities*

The aim is to sustain the EMRP over time; ensuring objectives remain relevant, by:

- Updating foresight studies and roadmaps.
- Addressing sustainability.
- Benchmarking performance.
- Measuring impact.
- Promoting the programme.

### I.2 Management / governance of the Joint Programme

The EMRP will be managed and implemented solely by EURAMET e.V. ; a non-profit association of public utility according to German civil law (e.V.). EURAMET e.V. has been established to provide both an appropriate structure for the execution of the EMRP, and to meet the wider aspirations of the members to engage more effectively at European level. The entity has evolved from an earlier, informal (i.e. non legal status) EUROMET collaboration of some 33 countries plus the IRMM, part of the EC JRC. A key driver in establishing the new legal entity has been to maintain and strengthen the single voice for top-level metrology in Europe. Consequently EURAMET e.V. membership is open to all European NMIs, irrespective of their participation in the EMRP. Particular attention and care has been taken to ensure appropriate governance of both the wider membership EURAMET e.V. and the EMRP.

Decision-making for the EMRP is vested in a research committee, the EMRP Committee – with representation from the e.V. member from each of the EMRP participating countries – and subject to an agreed, weighted voting procedure. The EMRP committee decides on all scientific and strategic matters of the EMRP, i.e. on the thematic scopes of the Targeted Programmes and the over-all resource allocation. In addition, the Committee selects the evaluators and defines the evaluation criteria. Finally, it supervises the EMRP Management unit. The EMRP committee receives advice from the Research Council and considers stakeholder interests.

The joint programme will be managed on a day to day basis by a dedicated EMRP Secretariat, led by a senior and experienced EMRP Programme Manager nominated by the EMRP committee , and operated in collaboration with the EURAMET e.V. Secretary. The EMRP Programme Manager will work closely with the EMRP “chair” and the EURAMET “chair”. These will act as co signatories *vis-à-vis* third parties and both are accountable to the e.V. General Assembly. The EURAMET Chair has overall authority and supervises all of the activities of the association, consulting the EMRP Committee on EMRP issues. The EMRP Programme Manager, acting under the direct authority of the EMRP Chair, reports to the EURAMET Chair on all important matters related to the EMRP. The e.V. Secretariat, supporting the wider aims of the new legal entity, is based in Braunschweig, Germany. The EMRP Secretariat will be based, at the beginning, in NPL, United Kingdom. The total EMRP Secretariat staff will consist of some professional project officers and support staff. Operational management costs are limited to 4 % of the total programme value, and are met from direct cash contributions from those members countries of the e.V. participating in the Article 169. Costs associated with operation of the e.V. Secretariat but unrelated to the joint research programme will be met separately by all the e.V. members.

The EMRP secretariat is responsible for:

- The administrative, legal and financial systems of the EMRP.
- Preparation, implementation of the Calls and associated activities.
- Administration of pool of evaluators.
- Support to the different bodies of the EMRP.
- Coordination and communication between these bodies.
- External representation and communication for the EMRP in support of the EMRP chair.
- Monitoring of Targeted Programmes and associated research projects.
- Monitoring the capacity building measures, i.e. the grant system.
- Ensuring compliance with the contractual obligations of the EC.

Liability for EC funding is carried jointly and severally by the EMRP participating members of EURAMET e.V only, in accordance with an agreed protocol.

A support activity area will be "**information management**", with 3 main components **:**

- Supporting operations and communications of the e.V.
- Developing tools for, and disseminating knowledge relevant to the EMRP
- Supporting a register of projects

# II CONTEXT

## II.1 The global challenge for metrology

Industry, trade, and increasingly quality of life depend on precise, reliable and comparable measurements. Therefore the demands on metrology are steadily growing, and can be expected to grow even more rapidly in the future. The drivers behind this pressure may be considered threefold:

- traditional areas of industry are becoming more complex and are requiring broader measurement ranges and lower uncertainties;
- new areas of technology are emerging, e.g. nano-technology and biotechnology;
- areas in which the value of metrology is increasingly being recognised, though not in themselves new, e.g. chemistry, clinical medicine or food safety;

placing considerable stress on the traditional approach of advancing metrology mostly national R&D initiatives with occasional ad-hoc international collaborations.

## II.2 The international response

The International Committee for Weights and Measures (CIPM) – the governing body of the Intergovernmental Organisation of the Metre Convention comprising of 51 member States and some 20 Associated countries – addressed the challenges in a report "Evolving Needs for Metrology in Trade, Industry and Society and the Role of the BIPM", CIPM, 2003. The report concluded that: "The recent extension of requirements for accurate measurements into new fields and ever more demanding requirements for accuracy in traditional fields are very considerably stretching the capabilities of the NMIs and the BIPM. It is increasingly recognized that no one NMI is capable of providing the whole range of measurement standards and services that are now needed and that networking and close cooperation among the world's NMIs is essential". Whilst cooperation in the scientific comparisons of measurement standards is well established, there has so far been no attempt at strategically planned R&D collaboration. Furthermore in late 2005 the CIPM formally called on the international metrology community to increase its R&D resources and effort to work towards new definitions of the kilogram, the ampere and the Kelvin – in effect a redefinition of the fundamental units – and set out an ambitious timetable which places greater urgency on the launch of the EMRP.

## II.3 The European response

Europe collectively is the single largest contributor to and participant in world metrology, and the investment has a significant impact on the economy and quality of life within Europe. An independent study "The assessment of the economic role of measurements in modern society" carried out by Oxford University and commissioned by the European Commission[7] came to the following conclusion:

*"Our main finding is that this area of activity is extremely important in economic terms both because of the absolute size of measurement activity and because of the significant and wide ranging benefits it produces in underpinning technological innovation, growth, industry, trade and social programmes. Europe spends more than €83 billion per year, or nearly 1 %*

[7] DG-Research GROWTH Programme Contract No: G6MA-2000-2002; Geoffrey Williams *et al.*, Pembroke College, Oxford, 2002

*of EU GDP, on measurement activity from directly quantifiable sources alone. Adding in social spending on health, environmental regulation, safety testing, anti-fraud projects and normal day-to-day activity raises this figure considerably. By comparing these costs with estimates of the benefits of measurement, we can see that this money is well spent. Our econometric estimates of the economic impact of measurement activity show that this spending generates almost €230 billion of directly estimable benefits through application and from the impact measurement knowledge has on technology driven growth. This is equivalent to 2.7 % of EU GDP. Put another way, for every euro devoted to measurement activity nearly three euros are generated by way of directly estimable benefits alone. This is true even without taking into account the very large benefits to society in terms of health, safety and the environment, which would raise the benefit to cost ratios even further."*

"The increasing complexity and range of applications of advanced measurement science clearly required a step increase in impact from the available resources, particularly in the cutting edge R&D. Recognising the challenge, the European Commission organised a high level conference in 2002 in Warsaw entitled "An Integrated Infrastructure for Measurement". Commissioner Philippe Busquin emphasised the importance of overcoming fragmentation in research and called on the metrology community to up its game and contribute to the ERA.

In his words;
*"Measurement, testing and the definition of common standards, are essential elements in the establishment of a knowledge-based economy that the European Union is striving to build. In this context, a powerful European metrology infrastructure is crucial to ensure the proper functioning of the European single market and to strengthen the competitive position of European enterprises in the global marketplace."*

The European metrology community agreed that the fractured approach limits the impact and the enormous potential of European metrology research. Critical mass in R&D on important topics cannot be assembled nationally in many cases and some R&D is duplicated in different national programmes. Hence mechanisms were sought to enable the European metrology research community to address crucial activities requested by stakeholders not currently supported due to national budget constraints, to respond to new challenges, and to start strategic large projects above a critical mass threshold.

The metrology community formally responded in 2003 when the EC supported a feasibility study[8] examining the options for metrology in the context of the European Research Area. The study confirmed that strategically planned collaborative R&D was essential if the various publicly funded national measurement systems where to meet their objectives in the future. In 2005 the European Commission launched an ERA-NET[9] to establish the appropriate conditions for such collaboration with the stated objective of launching a joint European metrology research programme in FP7. The project has established the approach, built the appropriate consensus, developed structures, procedures and processes necessary for the EMRP. Furthermore it transformed EUROMET, an informal collaboration amongst the 33 European countries, into EURAMET e.V., a legal entity suitable for the execution of the EMRP.

[8] MERA: Metrology in the European Research Area – Contract No. G6MA-CT-2002-04012
[9] iMERA: Implementing Metrology in the European Research Area – Contract No. 016220

## II.4 The EMRP

Within the context of the EMRP the main strategy is to significantly accelerate and broaden the development of metrology as a cross disciplinary, scientific discipline which:

- is instrumental in the innovation process within the context of both the wider research community and advanced industrial development;
- supports EU policies by providing the technical basis for conformity assessment and regulatory requirements.

The EMRP focuses on three key approaches:

- A new approach for the metrology research community in which “grand challenges” are addressed by bringing the various strands of measurement science to bear on issues of European and international relevance. The key challenges have been identified. They relate closely to the priority areas of the Seventh Framework Programme, and will require input from the EMRP Research Council to focus resources in the most effective way on the appropriate metrology and measurement aspects.
- Developing cross-disciplinary solutions to solve direct challenges related to fundamental metrology, typically the fundamental constants and the redefinition of the SI units.
- Focused R&D within single metrology disciplines aimed at improving the accuracy of the realisation and dissemination of the primary and secondary units of measurement.

Liaison with the appropriate themes in FP7 is foreseen, as well as with European Commission’s Joint Research Centre, which is expected to participate directly in appropriate EMRP activities.

Currently a number of countries have only modest, or in some cases no national metrology R&D programmes. The EMRP will both disseminate and capacity build with these countries and at the same time tap into the pool of available expertise. Appropriate support mechanisms to achieve these aims are included in the Capacity Building section of the programme.

## ACTIVITIES

Metrology is a horizontal scientific-technical field which underpins almost all subject fields in natural sciences and engineering. It is a technically wide and multidisciplinary field under a common methodology – characterized by the scientific treatment of measurement uncertainties, mathematical methods, principles of traceability, international metrological structures and organizations which cover the SI system such as the International Committee for Weights and Measures (CIPM) under the Metre Convention. The EMRP addresses metrological research activities at the frontiers of measurement science in order to meet the most urgent industrial and societal needs.
Metrological research and innovation is usually addressed in a single-discipline approach along a scheme of technical fields given by the Consultative Committees of the CIPM and the Technical Committees of EURAMET. This approach is powerful in many cases, especially in the "classical" fields, and will be part of the EMRP. An increasing number of challenges, however, require a more multidisciplinary approach due to complexity of the topics. Thus coordination within the EMRP does not only mean coordination of national programmes in a specific field but also coordination of different research activities driven by a complex challenge.
Consequently, the activity areas of the EMRP are structured in

- Grand challenges for multidiscipline metrology (*health, energy, environment, new technologies*).
- Grand challenges on fundamental metrology.
- Focussed single-discipline and applied metrology.

## II.5 Grand Challenges

### Multidiscipline metrology

Grand challenges comprise multidisciplinary metrology research needed to meet key socio economic objectives in the fields health, energy, environment, and new technologies. These fields require a research approach that – driven by the challenge – integrates and combines various technologies and methods. However, the metrology research in Europe in these fields has so far been rather fragmented and not yet been strategically coordinated. In the EMRP, the existing research activities and capabilities, which are directly related to the above-mentioned fields, are combined, coordinated and supplemented by missing research needs.

The priority setting will be carried out in consultation with the Research Council representing the key stakeholders. The selection of fields reflects the character of metrology as a horizontal, underpinning research field with particular relevance for the 7$^{th}$ framework programme.

### *Health*

Metrology for health underpins the more reliable and efficient exploitation of diagnostic and therapeutical techniques and the development of new technologies, which is needed to improve health care and patient protection, limit costs and foster the competitiveness of the related European industries and services. In addition, legislation requires more and more substances and techniques to be covered by metrology such as through the in-vitro diagnostic medical devices directive 98/79/EC.
Metrology for health is not a "classical" field of metrology, and the concepts of comparability, uncertainty treatment and traceability are not widely appreciated. The quality of medical diagnostics and treatments is often poor and even creates risks for patients. Besides challenging research, collaboration with external experts, e.g. physiologists and patho-

physiologists, will be required to supplement the metrologist's expertise and efficiently implement the concepts in the relevant medical community.
In the framework of the EMRP, the most competitive metrological activities within the national research programmes, which are directly and solely related to health applications, have been collated and supplemented by new topics to establish a coherent multidisciplinary approach on metrology for health. The field of radiation diagnostics and therapy is covered in the focussed single discipline field of ionizing radiation.
The most urgent scientific fields include the following research challenges for diagnostics and therapy:

- The "virtual human" refers to a model of the human anatomy and the human functions as a comprehensive reference standard for manufacturers of medical instrumentation, medical science, modelling and education. Some of the necessary input data to these models of system biology, i. e. the (elasto-) mechanical, electrical, optical, thermal, etc. material property data are either not available or of poor quality leading to rather unrealistic results of the modelling. In addition, models will be validated by developing measurement methods and undertake measurements to obtain realistic in-vivo biomaterial data.

- The expansion of the range of "reference measurement procedures and reference materials of a higher order" is recommended by the JCTLM (International Joint Committee for Traceability in Laboratory Medicine), a joint body of CIPM, IFCC (International Federation of Clinical Chemistry and laboratory medicine) and ILAC (International Laboratory Accreditation Cooperation). Examples of immediate need that has been identified are C-Reactive Protein (CRP), prostate specific antigene (PSA), Cardiac troponine (cTnI), human growth hormone (hGH). The large number of measurands requires a consequent, network-type coordination of the national programmes including specialized research laboratories other than NMIs.

- *"From qualitative towards quantitative diagnostics"* refers to fields such as imaging and multimodal measurement procedures. These procedures are manifold and widely utilized in the health sector, however, diagnostical results are often interpreted only in a qualitative, subjective manner, thus limiting the value of these methods. Metrological research introduces quantitative and traceable measurements to overcome the limitations. A substantial part of the research challenges is related to the development of mathematical models and tools, and software.

- A basic requirement for improved measurements in molecular medicine is the identification and metrological validation of suitable biomarkers. These biomarkers are the backbone of molecular imaging methods (e.g. fluorescence microscopy, magnet resonance imaging, PET). The rapidly increasing field of alternative marker-free nonlinear imaging methods (e.g. sum-frequency, heterodyn-CARS microscopy) has to be considered as well.

- Diagnostical and therapeutical instrumentation employs a very broad variety of measuring principles, e.g. NMR, ultrasound, or electrical and magnetic biosignals. Metrological research is requested to improve their quality with respect to reliability, validity, comparability, and patient risk, and to drive innovation towards real-time and non-invasive measurements, or towards individually optimized drug delivery.

***Energy***

Ensuring a consumer oriented, reliable and sustainable energy supply in the face of increasingly scarce and expensive resources reflects one of the major challenges faced by society. Coupled with this is the requirement to reduce greenhouse gas emissions in power generation which could in-part be addressed by increased use of renewable energy sources, but could also be substantially dealt with by reduced energy usage through more efficient appliances, energy management and improved distribution efficiencies. One of the current challenges is to explore the different solutions for transforming the present fossil fuel energy system into more sustainable ones based on a wide range of renewable energy sources. This challenge for new sources of energy addresses new technologies as well as energy efficiency, security of supply, climate change (highly connected with environment and climate changes) and EU competitiveness.

The demand of comparative measurements, which is increasing for comparing the performances of all forms of energy, concerns the existing energy sources as well as the developing of future ones. Research will be used for the improvement of the measurement of the efficiency of the energy generation in electrical plants, thermal plants, fuel cells and renewable sources using chemical production, ocean wave, wind or solar sources. As an example for transport, the efficiency of the conversion of bio-ethanol with the second generation bio-fuels need research on thermal energy measurement converted in mechanical power. Progress in comparisons of energy efficiency of hydrogen and fuel-cells, synthetic fuel needs also better measurements and metrological standards. Capabilities have to be improved on the conversion efficiency of solar-powered energy systems for adding renewable energy sources to national power networks. It also includes better efficiency and safety of the current nuclear plants and the future nuclear fission project ITER.

The improvement of energy measurements is related directly to the saving that both producers and users can get from a better knowledge of the cost of energy on the side of the production as well on the consumption side. Current metrological standards for the measurement of energy of different kinds such as electrical, thermal or nuclear need to be improved for a better accuracy of the energy measurement at all the stages from the production (and before as gas or liquid flow for natural gas or fuel plants) to the use, better measurement of the gross calorific value of the natural gas. As an example, the basic improvement of electrical units at industrial frequency will allow a better measurement of the electrical energy on both sides: producer and consumer; It will lead to a better knowledge of the losses, a better implementation of the grids and service of the operators to the customers. The application or indirect use of energy should be also addressed: improvement of the standards used for the efficiency of lightings is such an example as well as for the characterisation of the quality of the electrical power.

The most effective way to address one of the energy challenges is to use less energy. A s a major proportion of energy used is to heat and cool buildings, simple innovative methods of improving energy use in the build environment are urgently required. The development of new or better sensors by the manufacturers for improving the efficiency and savings for buildings, services and industrial users will need improved standards, better calibration capabilities, modelling and comparability of the sensors. It leads to research in different field as temperature, humidity, optical radiations. The research also will cover an improved knowledge of the data related to thermal and physical quantities of materials for advanced modelling and optimization of industry processes, transport, thermal insulation and air conditioning. The safety of the current and new engines will be addressed: research on more precise mechanical measurements will reduce the safety margins (wind, steam and ocean wave engines) and make them cheaper and more efficient. It will ensure the development of new technologies for a better competitiveness of EU industries.

***Environment***

A key challenge facing the EU is the need to ensure continuous and sustainable growth whilst reducing negative environmental impacts. Many of the activities required to achieve this will depend on new stable and comparable measurement standards for environmental changes and the environmental performance of new technologies. These typically involve measurements at much lower levels and over longer timescales than are required to address other themes within the EMRP. The nature of the challenges faced in protecting the environment and in developing new sustainable technologies dictates a multi-disciplinary approach that will drive the requirement for research within the EMRP that brings together different disciplines within measurement science.

The results of the EMRP will underpin research carried out within the Environment and Energy Themes of the 7$^{th}$ Framework Programme. This will ensure that the community of scientists within the EU's Research and Innovation base (EU's R&I) have best access to the combined experience and capability of the EU's NMIs. Examples include:

- Activities performed across the EU to detect changes in the environment and to monitor the climate depend on the availability of a robust and stable measurement infrastructure. The EMRP will address the needs for:
  - Novel sensors and underpinning measurements for global surface and ocean temperatures and stable long-term trends in the composition of the ocean and atmosphere.
  - Provision of a distributed system capable of providing traceability for measurement data from global ground and satellite-based networks.

- Research into innovative new systems and technologies that mitigate environmental impacts. These require:
  - Internationally-recognised standards to underpin measurements of the flow and concentration of species regulated under the Kyoto protocol and EU's emission trading schemes.
  - Measurements that validate claims of high-efficiency transportation, construction and energy technologies. These include the energy efficiency and thermal performance of buildings and "zero-emission" vehicles.
  - The accurate determination of ionising radiation fields for transmutation of nuclear waste.

- Minimising future negative environmental impacts depends on the implementation of policies that encourage the sustainable use of energy and resources. The EMRP will develop new measurement capabilities for:
  - The assessment of environmental fate (the destiny of a chemical or biological pollutant after release in environment) in order to provide a basis for uniform life-cycle assessment.
  - The determination of the chemical-content of waste materials to facilitate sorting and re-use.
  - The validation of the long-term efficiency of carbon sequestration technologies.

- Improving the quality of life for European citizens by:
  - Developing metrology solutions for new real-time methods and networked approaches to assessing population exposure to pollution risks.

- Improving measurements standards for flow and for the detection of bio and chemical releases into the environment.
- Extending measurement methods for exposure to radioisotopes in the environment.
- Development of new measurement techniques as well as assessment and
- reduction strategies for acoustic noise in living environment.

***New Technologies***

**a)- Metrology for nanotechnology**

Nanotechnology is a key enabling technology. The driving forces behind are the demand for ever increasing integration, e.g. in electronics and information technology, as well as the possibility of achieving new functionalities which are not possible otherwise such as through nano-structured surfaces, photonic crystals, optical meta-materials, and nano-particles. In many cases such as in nano-electronics, quantum-mechanical effects prohibit a scaling-down of properties in micro systems and thus require new scientific approaches. In the EMRP, the following metrological key challenges have been identified:

- Scanning probe microscopy is the basic nano-technological tool for dimensional analysis of nano-structured surfaces and nano-particles for semiconductor manufacturing. The development and combination of different microscopic techniques such as scanning techniques like STM, SFM, SEM and optical techniques beyond the classical limits and using nonlinear effects (heterodyne-CARS, SHG) promise to increase sensitivity, quality of 3D images and chemical specificity.

- Nano-electronics, nano-magnetic and nano-electro-mechanical systems impose well-defined and rapidly evolving metrological needs: measurement of sub-nm length photo masks as part of the semiconductor roadmap, nano-electro-mechanical systems, spatially resolved temperature profile of nano-electronic circuits with increasing structural density and clock frequency, or electro-magnetic properties of novel data storage media such as MRAMs.

- The manufacturing of nano-materials with novel functionalities such as nano-tubes and fullerenes requires metrological support through traceable characterisation. In addition nano-particles such as combustion products impose health risks. Thus metrological research towards traceable measurements of toxicity, shape, size, size distribution, chemical identity of nano-particles will be part of these activities.

**b)- Security-related metrology**

Metrology is capable to provide the growing public security needs with measurement instrumentation at the technological frontiers. Confidence in validation is a primary requirement in the acquisition and management of biometric data, for identification and authentication of individuals. Security-related metrology in the EMRP includes development and characterization of novel methods for the detection of hazardous materials using neutrons and by chemical methods. Another research option is underpinning quantum cryptography by entangled photon-sources which are also of interest in radiometry, and by validation procedures for information integrity, which also affects legal metrology.

The Terahertz (THz) region is the last part of the non-ionising EM spectrum to be exploited technologically. An emerging THz industry is developing rapidly in the EU. Major drivers for this rapid growth are – besides security applications – medical imaging, biological screening, e.g. of toxins in the atmosphere, and biological and pharmaceutical spectrometry of solids/liquids. At present much of this activity could not yet provided with metrological support, although requested by industry. Traceability will be provided through the EMRP.

## II.6 R&D for fundamental and applied metrology

### *II.6.1 Grand challenges on fundamental metrology*

Over the last decades, discoveries associated with new technologies, mainly in quantum physics, originated important changes in the world of metrology, in particular for fundamental metrology. They concern both the realisation of the base SI units and the possible redefinition of some units which could lead to an improved International System of Units (SI). The present trend is to connect directly current SI units to fundamental constants (as it has been done in the 1980s by fixing the velocity of light *c*, for a new definition of the metre), different proposals being discussed at the present time. Whatever it may be decided, the definitive choice must wait the consistent results of some current experiments, and the SI system should keep its coherence and consistency.

The International Committee for Weights and Measures (CIPM) and the related Consultative Committees, has strongly encouraged the National Metrology Institutes (NMIs) to direct their efforts towards a more accurate determination of the values of the fundamental constants and set up experiments for the realisation of the units of mass (kg), electricity (A), temperature (K) and amount of substance (mol). This will permit the CIPM to propose, in the future, a redefinition of the SI fully based on fundamental constants, as Planck, Rydberg, Avogadro and Boltzmann constants, the speed of light, the charge of electron or the fine structure constant. The universal nature of these constants allows relationships to be found between them, and it appears that some of the experiments are strongly interconnected as well as the possible new definitions. Supporting work will include "*Mise en pratique*" and dissemination of the units related to the new definitions.

The new definition of the kilogramme could be based on the Planck constant or the Avogadro number. Both experiments are based on different physical principles and require knowledge in wide areas of science like atomic interferometry, laser spectroscopy, physical properties of materials, nanotechnologies, etc., showing the multidiscipline research linked to one unit. A possible new definition of the kilogramme via the Avogadro number will demonstrate a direct link on the definition of the mole, and in consequence great changes for the field of chemistry.

The well-known developments and performances on atomic clocks allowed the new definition of the metre based on the speed of light ; due to the high level of accuracy, the measurement of time became the leading edge of metrology. To support emerging applications in telecommunications, transport and space, to increase our understanding of universe through tests of fundamental physics, and to improve the determination of some fundamental constants, new generations of frequency standards (and atomic clocks) in the optical range and nuclear transitions are currently under consideration, and will contribute certainly to an evolution of the definition of the second.

Considerable efforts have been realised to the measurement of light by non linear optics and research on quantum efficiency of detectors through correlated photon counting. A new challenge for photometry could be the determination of the candela by a number of photon.

To summarise, It is clear that quantum physics becomes an important domain which applications could be essential for the world of metrology, in every fields. A consequent number of medium and long time research could be initiated, and present developments strengthened. The activities proposed are presented in the following.

- **A first activity concerns experiments regarding the possibility of redefining the kilogramme and eventually the mole**. Two main routes exist related to those redefinitions: the so-called watt balances - linking electrical and mechanical units -, and the Avogadro constant - using silicon sphere and needing transverse R&D activities in many different metrology domains.

- *Avogadro route*

A new evaluation of the Avogadro number, in the objective of participation to a new definition of the kilogramme, puts stringent demands on : i) surface analysis techniques, in particular x-ray and optical vacuum interferometry for the measurement of the atomic lattice constant of silicon crystal; ii) dimensional metrology for the evaluation of the volume/diameter of a silicon single crystal sphere and to get a precise knowledge of the thickness of the Si oxide surface layer; iii) high precision temperature measurement. Some others crucial points could be material properties, surface effects, Si isotopes or studies of weighting transfer vacuum/gas.

- *Watt balance route*

The watt balance experiments could link the mass to the Planck constant and can, thus, open the way to a new definition of the mass unit kilogram based on a fixed value of the Planck constant. Several institutes are working on a realisation of the kilogramme by means of watt balances, comparing mechanical power to electrical power. Among extreme and accurate measurements to be performed, new materials may be characterised to elaborate specific mass transfer standards corresponding to experiment requirements, and accurate determination and/or feedback of the speed of motion of a moving coil may be implemented, to cope with possible non-linear effects in the interferometers involved.
Finally, the development of new set-ups on electrical quantum standards, specific electronic devices, and on novel gravimetry technology may contribute to reach the target of redefining the kilogramme at the $10^{-9}$ uncertainty.

**- The present, classical definition of the ampere is not suitable and indeed unused.** The possibility of a redefinition of the ampere based on the elementary charge, will be a step change in electrical metrology. Single electron tunnelling (SET) experiments are of great interest to reach this target, the basic electrical units would then be defined by fundamental constants and realised by quantum standards. An important milestone on the way to a redefinition of the electrical units is the verification of Ohm's Law at the level of quantum standards to give the proof, that quantum standards for voltage, current and resistance can be operated with the desired accuracy. The direct path via current (~1 pA), voltage (~ 1 V) and resistance (~ 10 kΩ) necessitates an amplification of the current by several orders of magnitude to achieve a voltage drop corresponding to the output voltage of Josephson voltage standards, which can be compared with the desired accuracy. A possibility is the use of cryogenic current comparators known for their very accurate gain. The charging of a capacitor with an exactly defined charge offers an alternative, because voltages in the order of 1 V can be easily obtained.

- **Fundamental research is requested for a new definition of the temperature unit, the Kelvin, based on a fundamental constant (Boltzmann constant: $k_B$)** in order to receive an "eternal" standard absolutely stable in space and time. A revision of the actual temperature scales dating from 1990 and 2000 should be performed after 2010, as well, including advanced results of research on primary thermometric standards
The current definition of the kelvin relies upon the realisation of the triple-point of water and is therefore is limited by the properties of a material substance. By redefining the Kelvin in terms of the Boltzmann constant, $k_B$, significant improvements over the whole scale can be attained, both in uncertainty and in thermodynamic consistency. Any future redefinition would, to provide continuity, have to be linked to the current International Temperature Scale of 1990, ITS-90 and this would be done through the development of the so called "Mise en pratique" for the Kelvin. At the moment several routes are investigated:

- *Acoustic Gas Thermometry (AGT)*

The same measurement method usually used for acoustic thermometry, which is based on the detection of acoustic resonances of a cavity, will be applied to a new determination of the Boltzmann constant, when operated at the temperature of the triple point of water. The measurements will be performed in a new type quasi-spherical resonator filled with pure gas. Its dimensions will be determined by microwave resonances very accurately in order to calculate the sound velocity from their wavelength. By now, for a typical 100 mm diameter resonator, diametric measurements of better than 100 nm uncertainty are required.

- *Dielectric-Constant gas Thermometry*

The existing dielectric constant gas thermometer, up to now operated at low temperatures, will be modified for the use at the triple point of water. By optimising the capacitor design and measuring its compressibility *in situ,* the uncertainty contribution to the determination of $k_B$ will be decreased at least by an order of magnitude compared to the present state. To achieve such a target, an uncertainty less than 1 ppb is required for the capacity measurement. Further progress is necessary in the pressure measurement using large area piston gauges as primary standards. Here, a calibrated precision high pressure balance with uncertainty less than 1 ppm is required. Thus, multidiscipline efforts are the ingredients of a successful result.

- *Spectroscopic method*

Recording the linear absorption spectrum of an ammonia rovibrational line in the 10 µm region at the temperature of triple point of water will open the possibility to extract the Boltzmann constant from the width of the resonance. The aim is to build a new spectrometer with higher performances in order to improve the determination of $\boldsymbol{k_B}$**,** by two orders of magnitude. Besides the standard method of linear absorption, other detection methods like hederodyne detection and dispersion spectroscopy will be considered.

- Over the last four decades, **time and frequency metrology** has been dominated by frequency primary standards working at microwave frequencies. These standards are improved to their theoretical and/or practical limits. Future clock experiments are investigated: optical clocks from neutral atoms to ion trapped set-ups, or clocks based on nuclear transitions.

For the moment, it is desirable to study as many potential atomic reference transitions as possible, a “best of all” candidate being not yet defined. In parallel, these instruments will be brought to a level of reliability similar to today’s microwave clocks, which again requires considerable and challenging improvements to local oscillators, laser stabilization, atom manipulation techniques, and optical frequency measurements based on frequency combs.

Beyond optical clocks, the pursuit for even higher frequencies will lead to instruments based on nuclear transitions. However, considerable technological achievements will have to be accomplished to open the road to these developments. Following the general tendency in metrology to connect the definitions of the base units to fundamental constants, calculable systems will also be investigated. At present the question has been left open as to whether a new definition of the base unit of time, the second, should be based on an arbitrarily designated transition (microwave, optical or nuclear) or on a calculable system linking the second to fundamental constants.

- **The candela** is qualified sometimes as a physiological unit, being related to the sensitivity of the human eye to the wavelength. Single photon source and detector characterization including photon counting from very low levels to high levels could be investigated. A redefinition of the SI base unit the candela in terms of photon number will require a demonstration that this method is consistent with existing techniques to at least the $10^{-5}$ level.

### *II.6.2 Focused single discipline and applied metrology*

Single discipline metrology is still the most powerful approach to address the challenges of most of the EU citizen in terms of quality of life, trade, commerce and safety. Extended to applied metrology, it covers the main needs of the subject fields of physics and chemistry when ensuring traceability of measurements and developing new standards and measurement techniques for the benefit of the EU industry and the citizen. This “classical field” approach allows to go deeper in the specific research needed in order to meet the most industrial and society needs. It underpins the 7th framework programme and will be coordinated by the EMRP committee in order to not overlap the research performed for the great challenges.

**Ionising Radiation**

In a long term perspective of research in the field of ionising radiations, the activities may be divided in three different but connected areas:

- Metrology for new radio-diagnostic and radiation therapy modalities;
- New physical concepts and metrology for quantifying radiation interaction with matter;
- Metrology for novel radiation sources.

The tendency to employ ***new diagnostic and therapeutic modalities*** regardless of a lacking metrology has persisted right up to the present time. Modern examples are forms of the Intensity Modulated Radiation Therapy (IMRT), in particular tomo-therapy, certain forms of brachy-therapy and the use of protons, heavy ions and neutrons for therapeutic purposes. Similarly, diagnostic procedures like CT, NMR, PET are frequently used at face value, without having given evidence that they are capable of presenting the location of organs free from artefacts down to a millimetre scale or even below, as it is now frequently requested. The investigation of interaction processes of ionizing radiation on the scale of a DNA-molecule will provide the key for a better understanding of the effects which are today referred to by the term of biological effectiveness. In the future, the optimisation of a radio-therapeutic measure will include the deliberate choice of the best suited kind of radiation (photons, electrons, protons, heavy ions) as well. The understanding of these effects will allow for a direct comparison between exposures to different kinds of radiation without the need to refer to empirical equivalence values as used today in the administration of doses from different types of radiation. Novel types of radiation sources will be the basis for further optimizing treatment methods provided they are backed by the necessary metrology.

On the diagnostic side, methods are required which permit reliable diagnoses avoiding any unnecessary patient exposure. To this end relevant components of diagnostic equipment need to be characterised in their dose sparing functionality. Examples are artefact-free geometrical localisations of organs, particularly in the context of image guided techniques, image receptor sensitivity, modulation transfer functions, detective quantum efficiency and the capability of measuring correct electron densities, to name some important features. In functional imaging, like e.g. PET, diagnostic results need to be traceable to the SI system, this applies also for the measurement of quantities like blood velocities, nerve currents etc. need to be traceable to the SI-system.
Recent rapid advances of three dimensional Conformal Radiation Therapy and IMRT have created an urgent need for the introduction of high resolution three-dimensional methods of dosimetry. By escalating the dose to the lesion, while minimizing the dose to the surrounding healthy tissue all modern treatment techniques make deliberate use of steep dose gradients, regardless whether external therapy or brachy-therapy is employed. Problems associated with these techniques are the absence of proven methods for specifying the radiation quality, the energy and angular dependence of the detectors' responses, unwanted, detector-

specific properties like fading of the radiation induced (latent) signal. Additionally, organs or tissues moving during the radio-therapeutic procedures require new treatment methods. In such modalities, often referred to as 4D, the beam is gated, e.g. by the breathing of the patient. Existing protocols on clinical dosimetry for radiation therapy are only designed for simple standard situations and unsuited for IMRT conditions, let alone 4D applications. The dosimetry based on portal imaging and with advanced detectors like radio-chromic films, polymerizing gels, alanine, TLD, scintillators and liquid ionisation chambers has to be improved in order to achieve accurate dose mapping. With the support of Monte Carlo radiation transport simulations secondary standards suitable for a reliable dose mapping under routine clinical conditions need to be established, which also allow the verification of treatment plans.
Having achieved this goal will open the window for the development of new radiopharmaceuticals, sources and external beams which in turn are better suited for an optimized delivery of any desired dose profile. The achievements of metrology will enable European manufacturers of medical devices to improve their products systematically. Apart from the undisputed improvement of the quality of life associated with an increasingly successful fight against cancer there will also be an important economic offspring of these activities from which the European economy will draw its advantage.

***A new challenge of radiation metrology is to define physical quantities*** which are, first, easily measurable and are, second, based on the track structure of single ionizing particles as well as on the properties of radiosensitive nanometric structures in nano-technology, nano-electronics, and bioscience including radiation therapy and radiation protection. To tackle this challenge, systematic studies are necessary aiming at determining more accurate interaction data of ionizing particles with matter, the detailed investigation of radiation damage to nanometric structures like nano-tubes or new materials based on silicon, and the development of specific Monte Carlo methods. They will allow to simulate both the track structure of ionizing particles and the damage to complex nanometric structures. Based on such investigations, the correlation of track structure with radiation damage and the definition of new appropriate measurable quantities characterizing this connection will be possible. This enables the development of new dose concepts and appropriate radiation detectors. They need to be closely related to particle track structure and radiation damage and should be well suited for characterizing the quality of ionizing radiation in medical applications, in nanometric bio-systems, and in nano-technology . A good starting point to metrology of the future is the break through of experimental nano-dosimetry a few years ago. It was proved, firstly, that the formation of ionization cluster size in nanometric volumes due to single particles can be derived from highly sophisticated measurements based on single-particle counting and, secondly, that the frequency of ionization cluster size is strongly correlated with radiation damage to nanometric structures like the DNA.

Concerning ***novel radiation sources***, some of them already exist, or soon will, while others are still in a very early state of development. A specific example of a new type of radiation source is the Peta-watt (PW)-laser which can produce several types of radiation fields; electron, gamma, proton, and neutron beams. Hence, possible applications are of a wide range. Furthermore, devices for scanning individuals or vehicles, new on-site radiography sources, and applications for fusion facilities etc. are already in use and
new applications are emerging rapidly. Amongst the characteristics of the accelerator-based radiation fields that will need to be measured are: the time structure for pulsed sources, the energy distribution, and the particle composition.
The first target, “Traceable instrumentation for characterising new sources”, is concerned with accelerator-based sources which already exist at some stage in the development process, and the metrological needs can be defined reasonably clearly. For example, faster types of pulse-mode detectors, probably scintillator detectors, are required to cope with the pulse characteristics of the source. In fusion diagnostics, there is a strong demand for improved and traceable instrumentation.

The second target, “Realisation of new devices for measurements on future novel accelerator sources”, is concerned with new radiation sources whose characteristics are more difficult to predict. The metrological requirements are not fully understood and it is not yet completely clear what types of instrumentation or standard fields will be required.
The third target, “Metrological standards and quality assurance”, represents the completion of both the metrological work and novel source development work. One of the items under “experimental realisation” is concerned with the development of portable devices producing ionising radiation, which will be performed by teams outside the metrology sphere.

**Electricity and Magnetism**
Electrical measurements have a great impact on nearly all areas of research and development, industrial activities and quality of life. Non-electric measuring quantities are converted into electric quantities already at the sensor level and as such are transformed, processed, stored and transmitted. Therefore, electrical metrology plays a key role and underpins further development in FP 7 fields like health, ICT, nanotechnology, energy, environment, traffic and security. The following key research topics were identified:

- ***Enhanced measurement capabilities for quality and efficiency of electrical power***: Society will be faced by future energy challenges. Increased demands combined with insecure supplies and ageing power plants will potentially cause energy shortages in the next decade. Coupled with this is the requirement to reduce green house gas emissions which could partly be addressed by increased use of renewable energy sources, but also by reduced energy usage through more efficient appliances, energy management and improved electricity distribution efficiencies. Ensuring a consumer oriented, reliable and sustainable supply of electric power in the face of increasingly scarce and expensive resources together with the deregulation of the energy markets demand enhanced measurement capabilities for quality and efficiency of electrical power, and monitoring, and protection of power grids and apparatus.

- ***Improvement of EM field measurements:*** Due to the pervasive use of broadcasting devices, particularly for mobile applications, the ambient level of RF power, particularly in cities and work places, is rapidly rising in the EU. There is a need to address the health and safety issues that this development raises, because a safe radio frequency environment and issues relating to electromagnetic compatibility (EMC) are a requirement for the successful implementation of these technologies. The required metrology is traceable Specific Absorption Rate dosimetry and traceable EM field-strength measurements at all frequencies that are in wide-spread public use. This is essential to meet the requirements of the Physical Agents Directive and ensure more general safety for EU citizens. Mobile communications, RFID, tagging, remote sensing of environmental changes, earth observation, management of traffic flow, driver assistance in vehicles, monitoring of food quality, etc. will be making use of ‘wireless’ or broadcast RF and microwave signals. In addition to the EMC issues, metrology associated with the implementation of these technologies will also be required.

- ***Extension of the frequency range into the Terahertz region*****:** Information and communication technologies will play a key role for both the economic and the socio-cultural development of society. Ensuring the required flow of information, at any time and at any place, means providing the necessary metrology for future high-speed information and communication systems. As new multimedia applications like online training, peer-to-peer collaboration, telemedicine or virtual reality environments emerge, the need for both, new smart system architectures and significantly increased bandwidth, arises. The availability of unoccupied bandwidth in the lower electromagnetic spectrum diminishes from year to year. In contrast, the demand for higher data rates requires an increasing frequency band. Therefore, the extension of the operation frequencies of communication systems into the terahertz frequency range will be unavoidable.

- ***Development of ultra-sensitive characterisation methods for nano-structured devices and materials***: Nanotechnology is a major driving force of economic growth in the EU. Tomorrow's nano-electronics and nano-magnetic technology requires ultra-sensitive electronic characterisation of nano-structured materials, components, devices and systems. This requires the development of ultra-sensitive measurement tools, which need to be pushed to the measurement and control of single quantum entities as the ultimate limit. Starting from today's scanning probe microscopy (SPM), the development will be directed towards improving the sensitivity of the different types of SPM to enable the measurement of extremely small electric and magnetic quantities, and ensuring traceability and comparability of SPM measurements, based on a variety of reference materials and standards for the different SPM techniques. Basic building blocks for the detection of single quantum entities will be metallic or semiconductor quantum devices which allow single charges and corresponding electrical potential changes and fractions of flux quanta and potentially single spins to be detected.

- ***Development of intrinsically referenced standards****:* For improved production and support to emerging technologies, industry has a need for intrinsically referenced measuring methods which allow best practice electrical measurements. Measurement standards presently in use can not meet this requirement, because they are defeated by environmental influences and change their characteristic properties with time. By contrast, intrinsically referenced standards such as electrical quantum standards are independent of environmental influences, time and place. They do not need periodic recalibration and, therefore, are available for calibrations all the time. Starting from the state of the art, improved quantum standards will be developed which allow electrical quantities to be traced back to fundamental constants. If transportable quantum standards would be available, the uncertainty of measurement and the down time of the reference standards of industrial calibration laboratories could be lowered, because on-site calibrations could be performed instead of sending the reference standards to a National Metrology Institute for calibration.

**Time and Frequency**

Time and frequency are the quantities which can be measured most accurately. Advantages in the realisation and dissemination of time and frequency are expected to have wide-spread impact on innovation, science and daily life. In this area, Europe can capitalise on wide-spread skills in such areas as atomic clock making, time scale generation, time dissemination, space technology, and network synchronisation. The following research focuses were identified for the EMRP:

- ***Development of novel atomic clocks with unprecedented accuracy***: To overcome the limitations of today's best primary frequency standards based on laser cooled caesium atoms, atomic clocks using transitions with frequencies in the optical regime or even based on nuclear transitions have to be investigated. To this end the potential of the different approaches such as single ions or large numbers of optically confined neutral atoms have to be explored in order to identify the best candidates for a future re-definition of the second.
  For this purpose the necessary experimental techniques are not yet available and must first be developed, such as suitable UV- or X-ray frequency metrology techniques, local oscillators, frequency dividers and frequency comparators. Portable and transportable frequency standards have to be developed that allow one to remotely compare the novel primary standards.

The novel clocks will also contribute to fundamental science. Basic physical laws, governing the atom - field interaction, the constancy of so-called “fundamental constants”, and questions about the structure of the Universe, are made accessible through most precise frequency measurements.

- ***Establishment of novel ways for time and frequency transfer*** capable to capitalise on the achieved accuracy of optical clocks: Time and frequency transfer based on the utilisation of signals of the Global Positioning System (GPS), and of Two-Way Satellite Time and Frequency Transfer (TWSTFT) signals are exchanged through geo-stationary telecommunication satellites. Improvement by an order of magnitude can probably be achieved by the utilisation of the GPS carrier phase and later the Galileo carrier phase in networks of stations, by the utilisation of higher chip-rates and carrier phase in TWSTF, and by the utilisation of the additional signals provided after 2010 by the modernised GPS and by Galileo, which will allow the real time determination of the propagation delays through ionosphere and troposphere. A combination of all such activities will reduce the time transfer uncertainty from its current 1 to 2 ns uncertainty to potentially 0.2 ns, and the frequency transfer uncertainty to $10^{-16}$ in relative units. Such values would be well suited to assess the performance of cold-atom fountains available within five years from now with $10^{-16}$ uncertainty by remote comparisons and could also support the first comparisons between optical frequency standards operated in different institutes.
In parallel frequency transfer through optical fibres promises a rich potential, provided that the resources for renting and operating dedicated fibres between major timing centres in Europe can be performed. Stepwise, the length of such fibre connections shall be enlarged, and the frequency transfer capability at $10^{-17}$ uncertainty for one day measurement times shall be envisaged. A $10^{-17}$ fractional uncertainty for optical clocks is envisaged for about 2015. Such development is pre-requisite for widespread application of such accurate frequency standards.

- ***Utilisation of atomic clocks for specific space applications*****:** Space applications require the realisation of (partially) miniaturised instrumentation which is more reliable than today’s typical laboratory instrumentation, such as microwave atomic clocks for space applications, laser sources for space interferometry and optical clocks in space. Operation of clocks in space and – at the same time – highly accurate comparison techniques should enable an accuracy of frequency standards in space and a frequency transfer capability at the level of $10^{-17}$ by 2020. The investigations will allow to explore the potential of two independent approaches namely to use the space clock as a reference or to compare the ground clocks via the space clock. In these two cases the space clock plays the role of a transportable clock of high stability. Space clocks and space-based time and frequency transfer will be required for deep space navigation, and will allow advanced solar system studies, gravity wave search and other experiments fostering the understanding of the universe.

**Photometry and Radiometry**

Novel optical metrology in photometry and radiometry is requested to underpin the rapidly developing optical technologies and new photonic devices, materials and surfaces – representing the background of the present “Century of the Photon”. Through novel optical technologies, research in photometry and radiometry underpins challenges in the health sector and safety sectors by optical diagnostics and monitoring (including Optical Coherence Tomography (OCT) and optical analytical technologies, such as Surface Plasmon Resonance (SPR) and Fluorescence Lifetime Imaging (FLIM)) as well as the conservation of natural and human environment by remote sensing and implementation of more efficient lighting and energy conversion. In addition, an important criterion for the selection of research challenges of the ERMP is to drive innovation in the growing European optical industry. The following fields need to be addressed most urgently:

- ***Novel optical radiometrical capabilities for industrial, quality-of-life and environmental applications.*** Better knowledge of innovative complex light sources, global environmental parameters, photo-biological effects or renewable energy will require new developments in optical radiation :
  - *3D Metrology for innovative optical light sources* by novel illumination and signal sources such as LEDs, OLED-arrays and displays to be characterised and calibrated with low uncertainty. The research challenges are the development of measurement techniques for large-volume and pixelled light sources, near-field to far-field transitions, and the development of camera-based photometry and radiometry.
  - *Radiometry for monitoring the environment* by the development of robust and cost-effective detectors and calibration procedures requested for environmental monitoring applications, including space-based earth observation of climate and water temperature. A long-term goal is to establish a primary SI-traceable standard utilising a "metrology laboratory" in space in order to overcome the limitations due to drifts which occur when equipment calibrated on ground is transferred to and maintained in orbit.
  - *Reduce demand for renewable energy* by increasing the efficiency of light-to-energy conversion of solar energy.
  - *Establishment of a unified radiometry from THz to EUV range* by the development of scanning techniques using Terahertz (THz) radiation in the long-wavelength regime and EUV lithography for the semiconductor industry in the shortest-wavelength regime, the most prominent drivers. In the optical frequency range various technical innovations require improved metrological capabilities. Due to the multi-dimensional character of the radiation quantities in many of the applications a variety of parameters has to be measured simultaneously, e.g., wavelength spectrum, power level, angular and spatial distribution, coherence, polarization or quantum state. The final goal is to provide highest level realisations of the basic and derived radiometric units combined with a rapid, low-cost dissemination via the calibration chains.

- ***Towards Quantum-photon based standards for optical radiation:*** the development and validation of quantum optical metrology tools for communication technologies, quantum computing and cryptography is a long-term goal of the EMRP. Single photon sources, detector characterization and application, will include photon counting from very low levels to conventional radiometry.
  High speed communication, quantum computing and processing rely on optical fibres and complex all-in fibre distribution systems. The development and use of such systems requires a complex characterisation in term of spectral, temporal and polarisation properties.
  A redefinition of the base unit candela as "quantum candela" requires novel cryogenic radiometers, single photon sources and detectors at the $10^{-5}$ uncertainty level.

- ***Physical measurements of visual perception for product quality and security purposes:*** Product quality requests a quantifying metrology on what was a subjective assessment of appearance. Manufacturers request a quantifying metrology in this new field for more cost-effectiveness, reliability and thus competitiveness. To replace visual perception for product quality, most of the physical measurement methods, standards, instrumentation, modelling and simulation have to be developed for appearance metrology including research projects in reflectometry, colorimetry, fluorescence microscopy, and fluorometry.
  The incorporation of human physiology in physical measurements beyond the spectral sensitivity of the human eye will be a great challenge of the EMRP.

**Thermometry**

Under the keyword of "thermometry" all subject areas are summarised which are related to measurement of temperature, thermo-physical properties, humidity and moisture and to characterisation of reference materials for those measurements.

Temperature is one of the most frequently measured physical quantities in science and industry. That implies that precise knowledge of temperature and related quantities is fundamentally important, for the development of new and more efficient production techniques saving energy and other resources and reducing waste, and for control of societal problems of environment, climate and security. Humidity is of similar importance as a critical parameter in various production processes and a key indicator in climate models. The main research and development in the field of thermometry and humidity are:

- ***Fundamental and Quantum based thermometry**:* Improvement of techniques for fabrication of temperature fixed points will complete the "*mise en pratique*" of the Kelvin by realisations of new high temperature fixed points. For this purpose, analysis of impurities and isotopes, studies on reference materials and developments of superconducting reference devices will permit to model thermal systems. Temperature amplifiers and vapour pressure scales representation between fixed points are also essential developments for the new International Temperature Scale (ITS).

  For the long-term future, quantum effects will be exploited to measure temperature and related quantities. Earlier, quantum effects have to be dealt with as the origin of disturbances to measurements, if the relevant volumes and temperatures fall below the quantum-critical values. In case the number of particles or excitations involved approaches low enough values, the definition of the temperature itself as a thermodynamic quantity becomes an object of study.

- ***Temperature measurement devices:*** The following priorities have been identified for the development of temperature measurement techniques for applications in safety and security, healthcare, environment, sustainable resources and high technologies:

  *- Rapid, low-cost sensor calibration.* Considering the permanently increasing number of sensors needed for test and operation of thermal and humidity devices the calibration procedures for this mass market must be optimized with regard to time, cost and accuracy. The developments will be closely coordinated with industry.

  *- New types of temperature sensors.* For special applications new types of highly specialised thermometers will be developed like multi-compartment cells for fixed points, novel high-purity and eutectic high temperature fixed points, low temperature radiation thermometers for remote temperature sensing and for detection of materials relevant to public security, thermometers with improved temporal and spatial resolution, stable high temperature thermocouples, noise and magnetic thermometers and others. There is an increasing demand for the application of small devices. Therefore, new configuration techniques like for micro or nano-electro-mechanical systems (respectively MEMS, NEMS) have to be applied including superconducting circuits to reduce noise and improve accuracy. High spatial resolution will be achieved by combination of appropriate thermal sensors with scanning tunnelling and atomic force microscopes.

  *- Thermal and THz imaging.* Both methods are on the advance in non-invasive medical applications as well as in non-intrusive security screening. The quality of their results is strongly dependent on small uncertainties of the devices applied and on their traceability to reliable standards.

- ***Characterisation of thermal properties of materials**:* For the design and construction of new technical devices innovative materials are essential. Their thermal properties like heat capacity, heat conductance, thermal isolation, melting, boiling and sublimation properties and others have to be determined precisely and the data should be easily available with a evaluated reliability. EVITHERM, a database with access via internet, has started recently with support of the European Commission, is operated now as a non-profit society and has to be extended considerably within the next future by initiating a lot of research for getting new data material. Prioritisation will be aligned with the new materials part of the EMRP and will concentrate on metrological issues such as quantities required to establish traceablility.

- Actions to monitor global warming will require increasingly accurate ***humidity measurements*** and interpretation of the results. Especially the quantification of water vapour is critical for climate models and may define essential actions against global climate changes. Optimisation of combustion and heat treatment processes across all industries can be reached by intelligent humidity monitoring. Humidity and moisture measurements and controls are essential for energy efficiency of buildings.
Determination of water vapour is important wherever organic, corrodible, or reactive materials are produced, treated, handled or stored. Production processes in pharmaceutics, foodstuffs, microelectronics are also often moisture-critical. New robust and accurate humidity sensors should be developed to meet the various technical specialities and the durability requirements in different production processes.

**Mass and related mechanical quantities**

Mechanics, which comprise quantities like mass, force, torque, pressure, acoustics, vibration, ultrasound and flow is key tool for industry, research and society because of their wide range of applications in aerospace, off-shore industries, robotics, micro and nano-technologies, manufacturing or even to support diagnosis in medicine. In consequence reliable and traceable standards are needed as well as research for their improvement. Four main research routes have been identified:

- Fundamental research in mechanics for physics, bio-technologies and pharmacology, with contribution to the new realisations and definitions of SI units.
- Innovative set-ups for new industrial and societal needs : realisation of new devices, sensors and standards in dynamic conditions (for aerospace, medicine, transport, etc.), pressure standards for ultra high vacuum (UHV) and extreme UHV conditions.
- Advanced techniques for traceability of flow units.
- Specific metrological developments in acoustics, ultrasound and vibration issues.

***Fundamental research in mechanics***

In the proposed experiments relevant to a new definition of the kilogramme (and possible contribution to a new definition of the mole), accurate measurements in extreme parameter ranges must be performed. The determination of $h$ or $N_A$ constants requires research on surface effects (for mass transfer) in vacuum or gas, on specific material properties and stabilities to elaborate new mass standards (Si, Au alloy, Ir, etc.), with specific studies on Si isotopes, lattice interferometry, density and volume.
The new areas of pharmaceutical research (proteins), biotechnology (cells) and related activities require mass and force metrology at a level of range and uncertainty which almost do not exist at the moment. New measurement capabilities must be developed to address atomic forces in the nano-Newton regime ($10^{-9}$ N to $10^{-12}$ N) and molecule masses in the nano-gram regime (ng), whilst getting in parallel dimensional information on the systems at nanometer level. It is possible to realise electro-mechanical systems to generate forces, masses and torques at these ultra-low levels, however accurate measurement procedures are still mostly missing. The research will embrace the realisation of new traceable standards and techniques for the users in the medical, the pharmaceutical and the bio-technological areas.

***Innovative set-ups for new industrial and societal needs***
In aerospace, medicine, production, transport or process controls, measurements are generally performed under dynamic conditions and often by use of automated systems. In addition, increasingly complex measurement configurations require the characterisation and the realisation of mechanical multi-component measurements. Traceable dynamic measurements should cover periodic and shock-like excitation for different measurands with large range of amplitude and frequencies, with decreasing uncertainty. High speed data acquisition and modelling are necessary to develop advanced dynamic and/or multi-component measurements.

With important applications in car industries, in engineering, in petrochemical and pharmaceutical industries, but also for elaborations of specific materials, the developments of new high pressure technologies and standards are required. Other applications such as in the semiconductor industry require better standards in the extreme ultra-high vacuum regime. Set-ups of residual gas analysis will be realised to answer to the needs of industrial process control and high technology products. The proposed research aims to reinforce the leading position and competitiveness of the European industry in that field.

***Advanced flow measuring techniques***
Advanced flow measuring techniques have their needs in the field of environment protection, assessment of efficient use of recourses and new technologies in the field of micro & nano flow applications. There are three main targets and research activities related to this:
The need to develop better measurement techniques to support the decreasing of the pollution and the reduction of emission which can be gaseous, to the ground or water courses.
The reduction of the uncertainty of the measurements in the applications by a factor greater than 3 and new resources (hydrogen, compressed natural gas,..) leads to the improvement or development of new standards. They have to be developed at several levels: primary standards, secondary and transfer standards; the research related to influence factors is also crucial for the metering systems.
As measurements of micro- and nano flows can be found in Biotechnology and Public Health, Space technology, Defence, Environmental protection, it is of importance to investigate the nature of flow in sub-millimetre ducts and to develop innovative flow measurement technologies on micro scale devices. The development of new primary micro flow facilities and standard methods is important for a reliable and successful implementation of micro- and nano science in future flow measurement applications.

***Specific developments in acoustics, ultrasound and vibration***
Acoustics emission and ultrasound are key tools widely used in industry for monitoring of safety critical structures in aerospace, oil and gas, pharmaceutical development, waste remediation or nuclear industries. In these areas, there is a need to develop methods of characterising acoustic signals generated by safety-critical events, and of quantifying the applied acoustics fields. Sound is indispensable for communication and noise is an important environmental factor. Ultrasound is also most frequently used in medicine for therapy, diagnostics and surgery, and in off-shore industries to work in deeper water. Three main routes for the EMRP have been be identified; healthcare, environment and high technology products :
- Various ultrasound applications in medicine, such as diagnostic and informed risk-assessments, surgical techniques, require development of capabilities for traceability of the acoustic fields and of *'in-vivo'* assessment of the impact of acoustic energy deposited in tissue with the important issue of protecting the patient through the application of lowest possible exposures. Safety issues for audible sound and ultrasound will become of greater importance since the sensibility to factors of living quality will continue to grow within the next decades, so major improvements of medical audiometry devices and novel diagnostic methods are needed.

- Metrological instrumentation for vibration in the very low and very high frequency ranges is required for various applications in industry, medicine, seismology, navigation and customer safety. Assessment and reduction of noise in environment, industrial processes and buildings is an important target, which is regulated by European and national directives and will play a major role in the future. Novel measurement techniques and methodologies will form the technical basis for new assessment methods of noise based on psycho-acoustic parameters. In vibration multi-component transducers used in production will benefit to reduce worker's exposure to mechanical vibration and shock.
- The development of miniature detectors, potentially based on bio-principles, will open new opportunities for the application in acoustical metrology. MEMS will become essential in acoustics and vibration, to evaluate dynamic response of products in integrated electronics, for example in high frequency technologies, or for sound measurement instrumentations. The research in the frame of the EMRP will focus on issues concerning their reliability and characterisation, including new methods of calibration, and their application to provide novel solutions to difficult noise measurement problems.
- New safety criteria for emerging auditory hazards from airborne ultrasound need to be established, underpinned by measurement standards for sound-in-air in the frequency beyond the limits of human hearing. In addition work is required to underpin objective methods of hearing assessment being used increasingly on a universal basis to screen the hearing of the whole population.

**Length**

Dimensional measurements play a crucial role in almost every aspects of modern life. From nanometre (nm) tolerances for sub-micrometer (sub-µm) device features like in semiconductor production to sub-millimetre tolerances on mechanical industry for large fuselage components: dimensional quantities are key parameters for manufacturing, process control and fundamental metrology and are of great importance in nanotechnology, ICT, transport, space and health area. Four key challenges have been identified in the field of dimensional metrology:

- ***Nano- and micrometrology*** : The possible hazardous effect of nano-particles has to be addressed and their control require measurement, classification and secure handling/manufacturing. Several current techniques (such as high resolution microscopy) need to be improved and further developments in order to take into account smaller wavelengths. Research will include the definition of models for the interaction between the probes and features of interest.

  There is a need in nano-particles standards to control smallest changes in nano-manufacturing processes, the response of metrology tools has to be well understood.

  The newly developed nano-sensors (e.g. based on nano-tubes) and nano-standards in the sub-mm range will require 2D (3D) instrumentation with nm uncertainty for characterisation and calibration. For these nano-standards, the potential of atomic lattices as well as self-organization of structures will be investigated. The necessity to improve displacement metrology with pm-accuracy will include research on x-ray interferometry, necessitating x-ray wavelength standards, and refined optical interferometry.

  The measurements with nm-accuracy over extended ranges of several 100 mm are required e.g. in ICT manufacturing processes. Future techniques like e.g. EUV-lithography put stringent requirements on relative positioning of tool components and on their thermal and long-term stability, too. Similar requirements apply for the surface form deviations of key elements involved in wavefront imaging. The calibration of standards over extended ranges, e.g. surface characterisation of large mirrors for synchrotron, require suitable reference instrumentation, possibly necessitating vacuum environment and application of self calibration techniques.

Multi-parametric metrology (i.e.: dimensional plus optical, electrical or magnetic properties) is required if feature sizes approach the nm-scale, where often new properties are observed which offer the potential to tailor new functional devices.

- ***Dimensional metrology for advanced manufacturing technologies****:* Future manufacturing of components with sizes up to about 10 m, increased complexity and reduced tolerances, requires ever smaller measurement uncertainties, shorter measuring time, increased information content and production integrated metrology. For this the following aspects have to be considered:

\- *New sensors* together with test facilities and methods that can verify their performance under a wide range of reproducible environmental conditions are to be developed;
*Materialized artefacts* based on the knowledge of the probe-workpiece surface interaction have to be developed to determine sensor characteristics.
\- *A next generation of measuring instruments* must be designed, such as X-ray tomography instruments, new multiple sensor concepts, new absolute interferometers using broadband light sources, laser interferometers and laser trackers with refractive index correction, and remote sensing (µ-GPS).
\- *New software* used for the handling of a huge number of data points to produce a comprehensive characterisation of the objects measured must be evaluated and assessed (e.g. by means of numerical artefacts), it will include the research on virtual instrument for a better understanding of the measuring instrument's performance (e.g. for the automatic evaluation of measurement uncertainty).

- ***Long-range measurement capabilities.*** There are different issues for this domain:

Accurate 3D metrology over ranges up to 100 m is required e.g. by aerospace industries. The verification of global mapping system (or localisation of specific buildings) will need a better uncertainty of the measurements as well as calibration of GPS based navigation systems.
Part of the answer is a better determination of the refractive index for interferometry and absolute distance measurement (ADM) techniques. The possible approaches are multi-wavelength refractive index compensation, use of next generation light sources such as waveband restricted femtosecond combs, improved interferometry data analysis by high speed digitisation and analysis of long path interferometer data at multiple wavelengths. The new techniques could lead to on line turbulence compensation (assisted by e.g. the use of adaptive optics) or virtual beam compensation.

- ***Dimensional metrology enabling progress in basic science****:* Dimensional metrology is challenged by requirements from basic science or research in other fields of metrology.

For instance in the Avogadro route to a possible redefinition of the kilogramme at the $2\times10^{-8}$ level, dimensional metrology is needed to determine the lattice constant ($u = 3\times10^{-9}$) and the volume ($u = 1\times10^{-8}$) of a macroscopic $^{28}$Si single crystal sphere by precision interferometry.
In the Watt balance route to the kg redefinition, the speed of motion during the moving phase of the experiment has to be determined with accuracies at $<10^{-8}$ level. For the determination of the Boltzmann constant $k_B$ targeted at the $10^{-6}$ level different approaches are followed by NMIs, each with specific dimensional metrology challenges.
Furthermore, precise angle metrology is crucial for the determination of $G$ and of $N_A \cdot h$, high precision γ-ray (crystal) spectroscopy and ring laser developments for geodesy/earth rotation monitoring. Satellite tests of the equivalence principle to $10^{-18}$ (STEP project) require high relative position measurement to $10^{-15}$ m of precisely manufactured test masses in space. Future space missions envisage the use of space-borne satellite based interferometers for gravitational wave detection. This requires so-called 'formation flying' of satellites, i.e. with six DOF position measurement and control

capabilities in space necessitating nano-thrusters as actuator devices. At the required levels of accuracy the metrology platforms must utilise ultra stable materials.
These examples underpin the need in research for better standards in most of the main areas of dimensional metrology as a constant improvement of instrumentation for interferometry, positioning or angle measurement.

**Metrology in Chemistry**

Metrology in chemistry is considered as one of the most rapidly growing fields of metrology, driven by the need for reliable chemical measurements in many fields of our daily life and requests from global trade and national as well as international legislation. The metrological approach has been remarkably successful in clinical chemistry, whereas urgent needs in food analysis and forensics could not been addressed so far. Problems and scandals in these fields of due missing reliable and precise chemical analyses are omnipresent.
The fast growth of the responsible consultative committee CCQM already being the largest CC of the Metre Convention is in itself an indicator of the increasing importance of metrology in chemistry on a worldwide scale. The importance of metrological research for chemistry in Europe in particular, can be directly related to legislations in clinical chemistry, food, and environmental pollution, which require new and harmonized measurement standards for a safer and healthier environment (see, e.g., 96/23/EC (residues in food), 96/62/EC (air quality control), 98/83/EC (drinking water), 2000/60/EC (water framework directive) or 98/79/EC (In vitro Diagnostic Medical Devices (IVD)-Directive) and many others).

Central task for the NMIs consequently is to establish an international primary reference network for traceability in chemistry with a research focus on emerging challenges in the fields of clinical chemistry, food, environment, and forensics. The huge number of different analytes to be covered requires a distribution of tasks among the European laboratories, making this field especially well suited for a coordinated approach.
The central aim of EMRP is to underpin this European reference network through research and development of primary methods and measurement procedures.
Research within the EMRP will focus on traceable measurements methods for analyte/matrix-combinations with increasing complexity such as large molecules like proteins and biomarkers (e.g. troponine), and those with decreasing detection levels, especially trace and species analysis of hazardous substances. Residues of veterinary drugs, pathogens, and toxins and also GMOs are key targets in food analysis. In forensics, indicators of drug abuse, hazardous materials relevant for public security but also the quality of DNA-identification need to be addressed most urgently. Another topic will be the toxicity of nano-particles. Multi-analyte, multi-parametric measurements become possible - and must be made traceable.

Isotopic dilution mass spectrometry is widely applied to the quantitative analysis of molecules. For small molecules and ions, optical techniques with rapid scanning high resolution optical spectrometers allowing for specific and sensitive detection can be developed, using high power cascade laser techniques, accurate wavelength selection using frequency comb techniques and cavity ring-down set ups. Application can be foreseen in the field of trace analysis of gases in the atmosphere, allowing for a better understanding of the role of organic trace gases in climate change processes up to the accurate measurement of the wavelength of electron transitions of trapped ions, allowing for the determination of useful invariants of physics.
In the field of larger (bio)molecules, techniques such as Surface Enhanced Raman Spectroscopy (SERS), ultra-fast fluorescence spectroscopy and ORD/CD bring new insights in molecular dynamics. Surface Enhanced Raman Spectroscopy (SERS) offers high potential for the marker-free, reliable and fast analysis of diagnostically valuable macromolecules. The potential of nano-structured substrates for the SERS analysis in molecular biology shall also be investigated in another topic in this context. Recent

developments show that SERS can be used for the identification and quantitative determination of bio-molecules even on a primary level. Largely improved results can be expected from optimized periodic nanostructures produced by nano-technological tools such as e-beam lithography.
In addition, new analytical technologies shall be developed such as “lab-on-a-chip” devices, remote sensing instrumentation, high throughput screening devices, and new technologies such as surface-, micro- and nano-analytical measurement methods or single molecule counting. Furthermore, spatially resolved measurements become more common and surface-, micro- and nano-analytical measurement methods are more widely applied. There is also an increasing demand for in-line and on-line measurement methods for production control such as traceable electrolytic conductivity for the in-line control of production lines in the pharmaceutical industry. Reliability of such methods based on comparable, validated measurement standards is a prerequisite for their safe and successful application, especially in the health sector.

**R&D for emerging metrology areas**

***Biotechnologies***
Metrology is of increasing importance to the biotechnology community and is in increasing demand.  The context is the need to create a sound international basis for accurate and reliable comparable measurements underpinning the development and exploitation of biotechnology by European industry. Thus the emerging field of bio-metrology is placing new and growing demands on the metrology research community which needs a co-ordinated European approach at this early stage to maximise potential. The specific requirements are to provide the metrology to ensure compliance with health and production related regulation, and to help Europe innovate through the development and validation of new and novel measurement methods. Reliable and valid measurement methods that are fit-for-purpose are vital to driving production efficiency, product safety and improved therapy and diagnostics. Bio-metrology is critical for three key areas:

- **Healthcare**: Prognosis, diagnosis, monitoring of disease susceptibility and progression, improved drugs, therapeutics and vaccines, functional foods and compliance with health related legislation and regulation.
- **Bio-production**: Improved bioprocesses, industrial biotechnology process control for monitoring and quality control, bio-fuels for sustainable energy production, biodegradable products, as well as novel functional food production.
- **Security**: Monitoring of toxic and pathogenic risks including allergens and bio-terrorism, traceable measurements for environmental directives, environmental clean-up and bioremediation as well as safe agri & aqua culture.

Research topics will range from developing reliable and fit-for-purpose measurement methods for health-marker molecules, simple biological molecules such as nucleic acids through to novel measurements of proteins and their interactions. This will head towards the demanding objective of comprehensive measurement of cellular identity, composition and behaviour. Furthermore, advances in bio-metrology will feed into and facilitate the emerging field of Systems Biology and in particular data integration and bio-informatics in order to aim for the ultimate goal of whole organism metrology.

Priority setting will take account of the need to underpin priorities as identified in FP7 and the spectrum of research will be aligned with related topics in the EMRP.

***Metrology for new materials***
Materials developments are pervasive in our lives as the building blocks for everything around us contributing enormously to improvements in health, the environment and wealth creation through, for example, modern medical implants, cheap renewable energy from photovoltaics or major changes in telecommunications. Material science is undergoing a revolution, with new materials "designed for function" offering the potential to generate products and provide services that would be impossible with conventional materials. However such materials, in particular higher performance nano-materials, bio-materials metamaterials and hybrid materials bring particular metrological challenges due to their very nature, scale and special properties and the combination of two or more functions in a single material. It is important to be able to quantify the complex interplay of the microscopic state and the resultant properties. Progress is dependant on our ability to validate and inter-relate our measurements in four areas:

- ***Physical-chemical properties****.* For example: Thermodynamic data (Gibb's energy), Thermal analysis (Tg, reaction energies), Electrochemical (mass transport).
- ***Structural analysis****.* For example: Microstructure and topographical characterisation (EDAX, WDX, EBSD, AFM), Non-destructive evaluations.
- ***Constitutive properties of materials****.* For example: material flow (rheology), mechanical properties (strength / modulus / fracture toughness at different scales)
- ***Modelling of materials****.* For example: Predictive modelling (molecular modelling, micromechanics), Model testing / comparability / validation.

Metrology priorities will include the development and application of traceable measurements and predictive modelling to structure, property and performance of materials throughout their lifecycle. There are major challenges in these measurements, such as the relationship between mapped, multiple property variations and micro-structural variations, including inter-comparison of different mapping techniques. These activities will provide the appropriate tools and techniques to aid innovative developments and ensure full, effective and safe exploitation of new materials.
Where measurement tools, techniques and validated data are needed for specific applications priority setting will take account the need to underpin both other metrology R&D areas and key priorities as identified in FP7, especially thematic area 4 - "*Nano-sciences, Nanotechnologies, Materials and new Production Technologies*" - and input from the analysis by the CIPM Working Group on Materials Metrology. The spectrum of research will focus on new, functional materials and will be aligned with related topics in the EMRP.

***Mathematics and ICT for metrology***
Already today, hardware and software as well as mathematical methods are integral parts of almost all measurement procedures and many measurements rely on information communication technology (ICT) for data acquisition, analysis and display. The next generation of metrology systems will rely on further advances of mathematics and ICT.
It is necessary, e.g., to develop reliable mathematical models, to enhance the capabilities for data analysis, to ensure the trustworthiness of complex software and to incorporate arising communication technologies. This will result in intelligent, self-learning, self-calibrating and error-tolerant, adaptive distributed systems. It will also become increasingly important to develop mathematical approaches to obtain measurement uncertainty budgets and ensure the integrity of the measurement processes for complex systems. Standard approaches fail to describe such systems and therefore more general concepts and guidelines are required to deal with these challenges. It is furthermore essential to enhance the trustworthy of software and measurement data by developing appropriate validation technologies and security concepts.

Research themes of the EMRP include:

- **Statistical Modelling**
  The focus in the early stage will be on Bayesian methods and Monte-Carlo simulations (including Markov chain approaches) for the foundation of uncertainty determination and key comparison analysis. In the latter stages advanced methods for statistical inference in complex systems and approaches for qualitative measurements and decision-making shall be developed.
- **Mathematical Modelling**
  Solution of inverse problems and optimization of measurement processes. Examples are solutions of Maxwell´s equation and multi-scale problem in materials, transport equations, atomistic modelling to determine material parameters, modelling of self-assembly and self-organisation as well as models for the life sciences linking different scales from bio-molecules to cells via organs up to whole organisms.
- **Simulation and Visualisation**
  Computer-assisted design of experiments ("virtual experiments") that includes modelling, optimization, sensitivity analysis, visualization and uncertainty issues. Uncertainty determination in systems described by more advanced models (differential equations, stochastic equations, inverse methods) which is needed for proper metrological treatment of the related experiments and shall be summarized in the guidelines of GUM revisions.
- **Data Analysis and Signal Processing**
  A wide set of methods such as filtering, multivariate analysis including classification tools, unfolding of spectra, linear and nonlinear principal and independent component analyses, artificial intelligence and neural networks, stochastic processes, are requested from other parts of the EMRP. Reliable software libraries and large-scale computational facilities need to be provided
- **Software validation in measuring systems**
  The large "fan out" of measurement standards and calibration services from NMIs requires that control, computational and data management processes reflect an appropriate degree of trustworthy. A software development and validation technology needs to incorporate metrological knowledge with its specialised requirements. Only on this basis the provision of metrological software that meets the requirements of quality and economic efficiency is possible.
- **Distributed systems and security of measurement data**
  Along with the steadily growing spread of distributed systems and remote techniques (Internet-based applications for metrology), the requirement of security of measurement data increases. Security techniques and integration of security features into metrological systems need to be provided that are appropriate for metrology. The increasing importance bases, in particular on expected advanced future system and communication architectures, as to be described by intelligent, distributed, error-tolerable and ubiquitous.

## II.7 Capacity building and Future EMRP Activities

Capacity building and future activities will address both long term direction, including issues related to sustainability, and increased involvement in R&D and knowledge transfer (over and above that built into individual Targeted Programmes). The theme addresses both the partner country NMIs and the wider world, specifically targeting NMIs from European countries that are not participating in the Article 169, and also University researchers and key stakeholders in metrology who are able to contribute significantly new ideas to the objectives of the joint programme.

### *II.7.1 Capacity Building*

*II.7.1.1 Rationale and strategy*

1. Resources will focus on building capacity that significantly enhances the national and collective capability to support the three core objectives, namely:
    a. Accelerating innovation and competitiveness.
    b. Generating data and knowledge necessary to improve quality of life.
    c. Providing better tools for the scientific community.
2. EMRP will be taking due account of the complex environment in which capacity building must be relevant and effective, namely:
    a. The very significant range of capability (in both depth and breadth) within the partner country national measurement systems.
    b. Recognising that capacity building is appropriate in many European countries with “emerging” metrology systems, even within the participating countries NMIs.
    c. Recognition that those European countries that do not currently support metrology R&D programmes/activities are still important actors, they disseminate the measurement standards developed by the R&D performers through non-primary national standards traceable to the primary capability. In return the wider European community relies on the measurements embodied in goods and services from these countries.
    d. Observing the need to avoid unnecessary duplication of capability.
    e. Recognising the need to intensify collaboration beyond the core NMI networks, particularly with those Universities and stakeholders working at the cutting edge of measurement science.
    f. Knowledge transfer activities are a *two-way* information exchange between national metrology institutes and metrology stakeholders (universities, practitioners, industry, government, regulators etc) in support of research and innovation.
    g. Recognising the need to embed the EMRP in the longer term into the fabric of the participating NMIs so that collaborative and coordinated research becomes the *modus operandi* beyond the period of the joint programme.

*II.7.1.2 Capacity building*

The metrology scientific capacity is currently limited by both the lack of suitably qualified researchers and limited opportunities for researchers who in many cases are working on any given topic in isolation and frequently in projects that lack critical mass. EMRP funds will play a key role in expanding the envelope of capability with a series of targeted actions.

*II.7.1.3 Researcher Grants*

These flexible grants will complement and in some categories be selected with the Targeted Programmes; they will be competitive and will be implemented under three unique banners each aimed at a particular aspect of capacity building:

- Researchers excellence grants:

In order to enlarge the number of organisations with capacities closely related to metrology, **researcher excellence grants** shall be made available to organisations and/or individuals from the wider researcher community in the Member States and countries associated to the Seventh Framework Programme. Each selected organisation and/or individual shall be associated to an EMRP project.

- Researchers mobility grants:

In order to develop the capacities of individuals in metrology through mobility, **researcher mobility grants**, shall be made available to

  - o Researchers from NMIs and DIs of participating States;
  - o Researchers benefiting, either individually or through their organisation, from a researcher excellence grant;
  - o Researchers from EURAMET Members Countries not participating in the EMRP, which have limited or no metrology research capability.

These researchers mobility grants shall enable the researchers to stay either in an NMI or DI participating in an EMRP project or in an organisation benefiting from a researcher excellence grant.

- Early-stage researcher mobility grants

In order to ensure sustainability in the cooperation between NMIs and DIs of the participating States and to prepare the next generation of experienced metrology researchers, **early-stage researcher mobility grants**, shall be made available to early-stage researchers from the NMIs or DIs of participating Sates to enable them to stay either in an NMI or DI, in an organisation benefiting from a research excellence grant or in another organisation participating in an EMRP research project at its own cost.

| EMRP funding | | | |
|---|---|---|---|
| **Types of funding** | **Eligible organisations** | **Eligible countries** | **Evaluation criteria** |
| **A. EMRP project (consortium)** | **NMI and DI*** | **EMRP participating States** | **Article 15 (1) of the Rules for Participation in the Seven Framework Programme** |
| **B1.Researcher excellence grants** | **Any organisation except NMi or DI** | **Member States and countries associated to the Seven Framework Programme** | **Article 15 (1) of the Rules for Participation in the Seven Framework Programme** |
| **B2.Researcher mobility grants** | ***From* :** **(1) NMI and DI or (2) an organisation benefiting from a researcher excellence grant (3) researchers from EURAMET member countries not participating in the EMRP which currently have limited or no metrology research capability** ***To* :** **(1) NMI and DI or (2) an organisation benefiting from a researcher excellence grant** | **Member States and countries associated to the Seven Framework Programme** | **Article 15 (1) of the Rules for Participation in the Seven Framework Programme** |
| **B3.Early-stage researcher mobility grants** | ***From* :** **NMI or DI** ***To* :** **(1) NMI and DI or (2) other organisations participating in the EMRP project (consortium)** | **EMRP participating States** | **Article 15 (1) of the Rules for Participation in the Seven Framework Programme** |

** EMRP participant NMI includes all NMI laboratories within a country that make up the national measurement system*

### *II.7.1.4 Education and Training of researchers*

Top-level metrology formation (education and training) for researchers is very specialised. It often requires special equipment and laboratories and for a specific topic at any given time in any given country the audience is very limited. Consequently in many countries there are either insufficient or no adequate formal training opportunities, with researchers left to learn hands on by trail and error, and by mentoring. The present capacity building measure aims to significantly accelerate and raise skills level amongst European metrology researchers by increasing access to such training. The more appropriate of the training measures will be adopted on a case-by-case basis.

- Development and delivery of joint training.
- Trans-national access to existing national training.
- Increased secondments and guest working to/from NMIs, industries, Universities, etc.
- Increased coordination and sharing of knowledge transfer activities between NMIs and with corresponding activities in other regions beyond Europe.
- Improved links between NMI websites and other metrology knowledge transfer activities.

*II.7.1.5 Metrology Knowledge Transfer, including education and training*

The aim is to improve the effectiveness of metrology knowledge transfer KT as a means of raising the level of measurement competence in the European Union and elsewhere. KT is a key element in a European Metrology Research Programme since new measurement knowledge, created in research, needs to be transferred to be useful (in research and also in promoting innovation, growth and welfare). KT is a two-way information exchange between NMIs and metrology stakeholders (universities, practitioners, industry, government, regulators etc). Metrology KT covers a wide range of measurement needs/subjects as well a broad spectrum of KT mechanisms. This calls for a specific, proactive coordinated action of metrology KT in Europe, over and above the usual knowledge transfer attached to any project.

The more appropriate of the following two training measures will be adopted on a case-by-case basis:

- Trans-national access to existing national education and training
- Development and delivery of joint education and training

*II.7.1.6 National links*

This measure addresses two key areas of national activity.
Firstly the promotion of opening access to national metrology research activities that will continue to be supported on a national level outside of the EMRP. Secondly the measure recognises that whilst the EMRP will deliver collaborative and coordinated R&D the significant capital investment in specialist laboratories and facilities necessary for that R&D falls outside the EMRP funding envelope. Programme owners and managers will be encouraged to increase trans-national access to specialist facilities and to consider of joint trans-national investment when commissioning new specialist facilities.

### *II.7.2 Future EMRP Activities*

A number of measures will be supported to ensure the long-term direction of the EMRP remains appropriate and responsive. The activities will provide the information necessary for the governance of the EMRP, and will also look into the longer-term institutionalisation and funding of the EMRP beyond the Commission funding period. Theses measures will include:

- Updating foresight studies and roadmaps as appropriate
  - This measure aims to ensure the prioritisation of R&D activities remains relevant during the lifetime of the EMRP
- Addressing sustainability
  - This measure aims to embed longer term institutionalisation of collaborative and coordinated research in Europe, including consideration of the funding of the EMRP beyond the Article 169 period
- Benchmarking performance
  - This measure aims to provide appropriate information to help improve the EMRP over its lifetime. Activities will focus on benchmarking of processes and practices
- Measure the impact of the EMRP
  - This measure aims to provide the indicators that will enable the success of the EMRP to be established
- Promoting the programme
  - This measure aims to provide support for activities aimed at promoting the EMRP and its benefits to the wider world.

## Acronyms

| | |
|---|---|
| ***EMRP*** | ***European Metrology Research Programme*** |
| AFM | Atomic Force Microscopy |
| AGT | Acoustic Gas Thermometry |
| BIPM | Bureau International des Poids et Mesures (*International Bureau of Weight and Measures*) |
| CARS | Coherent Anti-Stokes Raman Spectroscopy |
| CC | Comité Consultatif du CIPM (*Consultative Committee of CIPM)* |
| CCQM | Comité Consultatif pour la Quantité de Matière (*Consultative Committee for Amount of Substance*) |
| CEN | Comité Européen de Normalisation (*European Committee for Standardisation*) |
| CIPM | Comité International des Poids et Mesures (*International Committee of Weight and Measures*) |
| CRP | C-Reactive Protein |
| CT | Computer Tomography |
| DNA | Desoxyribo Nucleic Acid |
| DOF | Deoth of Field |
| EBSD | Electron BackScatter Diffraction |
| EC | European Commission |
| EDAX | Energy Dispersive X-ray micro analysis |
| EM | Electro-Magnetic |
| EU | European Union |
| EURAMET | European association (e.V.) of National Metrology Institutes |
| EUROLAB | The European Federation of National Associations of Measurement, Testing and Analytical Laboratories |
| EUROMET | European Collaboration in Measurement Standards |
| EUV | Extreme Ultra Violet |
| FLIM | Fluorescence Lifetime IMaging |
| FP | Framework Programme |
| GDP | Gross Domestic Product |
| GMO | Genetically Modified Organism |
| GPS | Global Positioning System |
| hGH | human Growth Hormone |
| ICT | Information and Communication Technology |
| IFCC | International Federation of Clinical Chemistry and laboratory medicine |
| ILAC | International Laboratory Accreditation Co-operation |
| IRMM | Institute of Reference Materials and Measurements |
| ITER | International Thermonuclear Experimental Reactor |
| IVD | In Vitro Diagnostic Medical Devices |
| JCRB | Joint Committee for Regional metrology organisations and BIPM |
| JCTLM | Joint Committee for Traceability in Laboratory Medicine |
| JRC | Joint Research Centre |
| KT | Knowledge Transfer |
| MEMS | Micro-Electro-Mechanical System |
| MRA | Mutual Recognition Arrangement |
| MRAM | Magnetic Random Access Memory |
| NEMS | Nano-Electro-Mechanical System |
| NMI | National Metrology Institutes |
| NMR | Nuclear Magnetic Resonance |
| NMS | National Measurement Systems |
| OCT | Optical Coherence Tomography |

| | |
|---|---|
| OLED | Organic Light Emitting Diode |
| PET | Positron Emission Tomography |
| PSA | Prostate Specific Antigene |
| RTD | Research Technology Developments |
| SEM | Scanning Electron Microscope |
| SERS | Surface Enhanced Raman Spectroscopy |
| SET | Single Electron Tunnelling |
| SFM | Scanning Force Microscopy |
| SHG | Second Harmonic Generation |
| SI | Système International d'unités (*International system of units)* |
| SPM | Scanning Probe Microscopy |
| SPR | Surface Plasmon Resonance |
| STEP | Satellite Test of the Equivalence Principle |
| STM | Scanning Tunneling Microscope |
| TLD | Thermo-Luminescence Detector |
| TWSTFT | Two-Way Satellite Time and Frequency Transfer |
| UHV | Ultra High Vacuum |
| UIMRT | Intensity Modulated Radiation Therapy |
| WELMEC | European cooperation in legal metrology |
| WDX | Wavelength Dispersive X-ray diffraction |