



PROJECT FINAL REPORT

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1 EXECUTIVE SUMMARY

As the new millennium dawned the European National Metrology Institutes were faced with what we now refer to as the “European metrology dilemma”. Demands for wider scope and greater precision from traditional stakeholders, the need to support emerging areas such as biotechnology and nanotechnology, and the greater demand from established areas such as food safety, clinical medicine, environment, with static public funding, required a paradigm shift in the way we operated. Recognising these challenges and the broader responsibility to effectively underpin other areas of science, to facilitate innovation and to support the expectations for improvements in the quality of our lives, the “Metrology in the European Research Area” series of projects were launched.

iMERA-Plus, the first “ERANET-Plus” launched under FP7, aimed at aligning and enhancing national programmes with European Commission support. iMERA-Plus was operated by the European Association of National Metrology Institutes (EURAMET), the Regional Metrology Organisation for Europe. EURAMET coordinates the cooperation of National Metrology Institutes of Europe in research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and of the Calibration and Measurement Capabilities of its members. Resources from the National Metrology Laboratories and the Designated Institutes from 19 European countries, plus the Commission’s measurement institute (IRMM), have been pooled within a single joint Call for metrology research projects. In total some 64.6 M€ of resources were brought together, with the European Commission providing 21 M€ of funding, the balance provided from the national metrology research funding in the participating countries. The two-step Call ran between May and December 2007 and pivoted around independent peer review and selection of the very best metrology research proposals. 21 Joint Research Projects (JRPs) were launched in four Targeted Programmes, each project chosen for the quality of science and potential to make a significant contribution in its field.

The SI and fundamental projects addressed some of the deepest challenges in metrology; providing answers for new standards that push forwards the boundaries in metrology for mass, current and temperature, light down single photon level and time to unimaginable small. The projects helped increase the precision and reliability of measurement at the very highest level, increasing our understanding of the fundamental constants and support the redefinition of some of the Units within the International System of measurements. Metrology projects within the health area aimed to underpin new diagnostic tools for early disease detection, increasing our understanding of bio-molecules and biomarkers, bio-species and ion activity underpinning clinical chemistry and clinical medicine. They accelerated the exploitation of new regenerative treatments and offered major improvements in the accuracy of external beam and implanted source cancer therapies. Research led to better measurement of field strength and specific absorbed dose for non-ionising radiation in support of the Physical Agents Directive, protecting workers from harmful electrical fields. The length and dimensional metrology projects addressed precise and reliable measurement for nanoparticle characterisation, and development of state-of-the-art traceable displacement measurements to drive the development of next generation ICT hardware. The enhanced capability developed in 3-D metrology will improve the manufacture of large precision objects such as aircraft components. Finally innovative techniques will overcome limitations related to variations in the refractive index of air in precise optical measurement techniques over multi hundred metre distances. Metrology projects in the electrical & magnetic area helped to underpin the reliability of power distribution as renewable generation increases its contribution to the grid, and also delved deeply into the esoteric world of nanomagnetism and spintronics. Electrical measurements are everywhere and although most people would never be aware of it new or improved quantum standards for AC current and improved Quantum Hall resistance measurements offer rewards far and wide.

Dissemination of the outputs from iMERA-Plus was actively pursued at both individual JRP and programme level with the publication of more than 300 peer-reviewed papers, hundreds of contributions to conferences and workshops, and the provision of guidelines and good practice guides. Outcomes have also been exploited through industrial or sector based ‘user committees’, through standardisation, reference artefacts and measurement services.

In addition to scientific integration and impact, financial and management integration and associated impact have formed key aspects of iMERA-Plus, leading to a step change in collaborative metrology research. Research within the Joint Research Projects has underpinned fundamental research, supporting the implementation of Directives, and facilitating the development of more effective, efficient and reliable measurement and processes within industry.

2 PROJECT CONTEXT AND MAIN OBJECTIVES

The iMERA-Plus project “Implementing metrology in the European Research Area – Plus”, was an ERANET-Plus project funded by the European Commission under the Seventh Framework Programme. Participants included 33 organisations from 19 countries plus the EC’s Joint Research Centre and the project was coordinated overall by EURAMET e.V. - European Association of National Metrology Institutes. Within iMERA-Plus, 21 collaborative Joint Research Projects totalling 63 million Euros were undertaken in 4 thematic areas, with just over two thirds of the funding provided by the participating Member States.

2.1 Background

Measurement underpins virtually every aspect of our daily lives, helping to ensure quality and safety, to keep us healthy and to help us innovate and keep our economy competitive. Our understanding of key issues such as climate change, the quality and safety of the food we eat, the air we breathe and the water we drink, and the goods we buy, all rely on our ability to make ever better measurements. In industry measurements are crucial, for manufacturing, process control, telecommunications, transport and many other sectors, not least to remain competitive. Our ability to measure defines the boundaries of possibility. What we cannot measure, we generally do not understand properly and we cannot make accurately nor control reliably. Sound data based on reliable measurements forms a cornerstone of evidence needed for successful policy making. Thus advances in the science of measurement – metrology – have a profound impact on understanding and the shaping of the world around us.

Practically all governments in advanced technological countries and many less developed countries support a measurement infrastructure because of the benefits it brings. In many countries national research programmes and activities respond to the demand for measurement standards of ever increasing accuracy, range and diversity, striving to improve that measurement capability. Although there are differences broadly all have the same three core objectives; to drive innovation, to support sound policy and regulation (and thus to protect both the citizen and the environment) and to provide ever better tools for other scientific disciplines. The measurement infrastructure and the associated research are managed and delivered via the National Metrology Institutes (NMIs). The NMIs are additionally charged with ensuring the international system of measurement, the SI, functions appropriately, including the primary realisations of the base units and the dissemination to stakeholders. In the modern global economy comparability of measurements and interoperability is crucial, with perhaps the most obvious example being the atomic clocks in the NMIs that form the basis of international time keeping, and with it communications, banking, navigation etc.

As the new century dawned pressures increasingly stretched the ability of the European NMIs to address stakeholder needs effectively, particularly in terms of cutting edge R&D. Regulation, quality of life, innovation and fair trade all require an effective and advancing metrology infrastructure. Demands for wider scope and greater precision from traditional stakeholders (typically industry), the need to support emerging areas such as biotechnology and nanotechnology, and the greater demand from established areas such as food safety, clinical medicine, the environment, and more recently security, required examination of the *modus operandi*. Many of the new or highest priority challenges affect most countries and require resources beyond those of an individual NMI or individual national metrology system. It was clear that realistic expectations on budget increases in the European NMIs would not be sufficient to resource the growing demands, stretching the available resources so far that there was a significant risk of becoming sub critical and thus damaging the excellence of the research carried out. Action was therefore required to begin to address the so called “European metrology dilemma”.

2.2 Towards iMERA-Plus

Around this time at a much more generic level the European Commission was identifying fragmentation between national programmes within the European research community as a major barrier to optimising the impact of the research effort in Europe. The then Commissioner for Research, Philippe Busquin, coined the concept of a common European Research Area (ERA) as a pre requisite for a step improvement in the impact from the investment in European R&D, and as a vital element in a successful knowledge based economy in the 21st century.

In late 2002, at a conference organised by the European Commission in Warsaw, entitled “*An Integrated Infrastructure for Measurement*”, Busquin emphasised his views of the importance of overcoming fragmentation in research and called on the metrology community to “up its game”:

“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 NMI community, led by NPL in the UK, responded immediately and within the EC’s 5th Framework Programme conducted a study “*Metrology for the European Research Area*” – MERA – which analysed the metrological needs for Europe at the beginning of the 21st century and considered options for the way forward. As well as confirming the prevalence of the “European metrology dilemma” the study concluded that the most realistic option to address the dilemma was to significantly increase the impact of European metrology research through much greater coordination and collaboration.

In April 2005, under the 6th Framework Programme, and as a direct consequence of the outcome of the MERA study, representatives from 14 countries plus the European Commission comprising 15 EUROMET members and 5 ministries together launched a 3 year ERA-NET “implementing MERA” (iMERA). The iMERA project enabled the NMI community to understand, plan and trial closer collaboration, and to develop the conditions and design the structures to enable the NMIs to conduct coordinated and collaborative metrological research in identified areas of strategic importance. Crucially iMERA included a dedicated work package investigating, in consultation with the European Commission, the potential for achieving the desired step increase by pooling national and Commission resources in a joint European metrology research programme (EMRP) utilising Article 185 of the European Treaty.

Unusually the iMERA project included not only NMIs but also a number of their funding ministries. Historically the funding ministries of the national metrology systems had little or no contact or knowledge of their counterparts in other countries. For the first time the iMERA project provided the opportunity for them to get to know one another, to develop an understanding of how each other operates, how priorities are established, the constraints on the funding cycles and the potential for encouraging collaboration. Two workshops were held during the project specifically to bring together those that “own” the national metrology programmes (generally ministries) and those that “manage” the metrology programmes (usually NMIs). These workshops were open to European countries that were not partners in the iMERA project.

One of the key outcomes of the iMERA project led to a sea change in the organisation of metrology collaboration in Europe. Beginning in the mid 1980s collaboration had been organised through EUROMET, an informal but successful body that brought together the national metrology networks. However it became clear that the step change in level of collaboration and coordination sought required a new body, able also to act as a dedicated implementing structure for a potential Article 185 and to engage more effectively at European level on a range of issues beyond the research agenda. Following a detailed consultation a new “not for profit” body “EURAMET e.V.” was established in January 2007 and incorporated in Germany. During the summer of 2007 this body took over responsibility as the Regional Metrology Organisation for Europe under the intergovernmental Metre Convention, and the EUROMET MoU was terminated.

In parallel with the establishment of EURAMET, over a two year period the iMERA project also elaborated the European Metrology Research Programme (EMRP). The aim was to develop a programme that would address the need to support innovation, quality of life and European policy and the scientific community incorporating the wider horizontal grand challenges in addition to the metrology sector specific needs, and with the ultimate goal of a programme that could be launched under Article 185 of the European Treaty. As preparation for this work EUROMET/EURAMET established a number of focus/interest groups for life sciences, biotechnology, new materials and software and mathematics, to address metrological areas not covered by the existing Technical Committees.

In developing the programme it was important to understand and incorporate the wider stakeholder needs and to source input from outside the metrology community. As part of the process consultation was undertaken through a series of stakeholder workshops and focus groups covering health, energy, environment and security. The workshops included representatives from the medical profession,

medical research council, pharmaceutical industry, Joint committee on traceability in laboratory medicine, power generation industry, oil and gas industry, an organisation involved in nuclear fusion research, environment agencies, universities and policy Directorate Generals of the European Commission. The second strand used as an input to the programme was an extensive roadmapping exercise undertaken by the EUROMET/EURAMET Technical Committees and new focus groups generating more than 40 roadmaps.

With the knowledge gained a dedicated work programme - the European Metrology Research Programme (EMRP), was published in early 2007. The EMRP addresses grand challenges in health, energy, environment and new technologies for nano sciences and security, plus R&D for fundamental and applied metrology and additionally some capacity building. The fundamental and applied metrology areas include ionising radiation, electricity and magnetism, related quantities including acoustics, length, chemistry, biotechnology and materials metrology.

As the European Commission's 7th Framework Programme was being developed it became clear in late 2006 that there was an opportunity for an EC funding bridging measure on the road to an Article 185. This mechanism provided the possibility of a one-off call for transnational research projects that would receive approximately one third of their funding from the EC.

The proposal for the iMERA-Plus project was submitted and was successfully evaluated and selected, securing 21 M€ of funding from the European Commission.

2.3 iMERA-Plus Objectives

In essence iMERA-Plus was the first step in switching metrology R&D from a broadly national-only activity addressing essentially national issues to a European activity bringing critical mass to bear and thus able to address major European socioeconomic issues.

The aim of the iMERA-Plus project was to increase coordination between existing national metrology research and development resources in order to:

- Execute R&D in metrology against strategic priorities at European level, including grand challenges.
- Create sufficient critical mass in the research teams to tackle the major metrology challenges.
- Increase the speed at which metrology solutions could be delivered, particularly in areas with pressing metrology requirements.
- Share costs and expertise between participating European National Metrology Institutes (NMIs) and Designated Institutes (DIs).
- Reduce duplication of effort across Europe, and avoid development of unnecessary parallel solutions.
- Increase the impact of metrology R&D, through identifying improved solutions, increasing uptake of solutions, and widening knowledge of research outputs.
- Address high-cost multi-discipline metrology R&D themes, such as the grand challenge of healthcare metrology, one of the thematic areas in iMERA-Plus.
- Enable a number of countries to launch a metrology R&D programme for the first time (Austria, Belgium, Romania, Turkey and Estonia).
- Open access for the collaborative teams to special metrology facilities available in just one or two laboratories.
- Increase generic collaboration and knowledge transfer between institutes.

The direct objectives of iMERA-Plus were to deliver a series of joint research projects (JRPs) within four of the Targeted Programmes within the EMRP. The project tackled a subset of four of the areas of most pressing metrological needs identified in the EMRP. These priority areas are sufficiently diverse to make best use of the wide expertise and capabilities within the NMI community, and the Metrology for Health TP addressed projects prioritised by socioeconomic challenges rather than the traditional metrology SI Unit discipline. Each TP selected covered an area identified as:

- Having urgent metrological needs identified in the EMRP programme.
- Being prepared and able to collaborate within the iMERA-Plus project timetable
- Having potential to demonstrate significant impact, both to the metrology community and to the EU as a whole.

Crucially the iMERA-Plus project also demonstrated proof of concept for the implementation of the full European Metrology Research Programme via a metrology Article 185.

3 MAIN S & T RESULTS/FOREGROUNDS

3.1 Call process and selection of the Joint Research Projects

The call and selection process for the Joint Research Projects was organised and overseen by the new “not for profit” EURAMET e.V. legal entity created in early 2007 from the informal EUROMET European metrology collaboration. iMERA-Plus was the first phase of the implementation of the European Metrology Research Programme (the EMRP) and the available budget was therefore not sufficient to open all of the topics identified in the “European Metrology Research Programme 2007”. The EMRP Committee, the EURAMET body responsible for the EMRP prioritised a subset of four so-called “Targeted Programmes” (TPs) from the EMRP for inclusion in iMERA-Plus. These four TPs addressed the core SI & fundamental areas of metrology research (TP1), metrology research underpinning the health sector (TP2), and metrology research for two so called “SI Unit discipline” areas, Electricity & Magnetism (TP3) and Length/Dimensional (TP4), these themes addressed an area of key importance to the international metrology community, a grand challenge area, and two areas of industrial and scientific importance where participation from a wide range of EURAMET members and associates was possible.

The institutes eligible to receive EC funding under iMERA-Plus had to be publicly funded for metrology as a recognised part of a national measurement system (typically the NMI, or DI), have existing appropriate metrology R&D expertise, and be willing and able to accept the duties and obligations associated with participation. Additionally, by exception, for countries launching metrology R&D programmes for the first time whose NMIs did not currently have an in-house R&D capability, the NMI/DI in partnership with the publicly funded R&D institute with metrology expertise who are assisting their NMI to develop specific R&D capabilities were also eligible to participate. The call was open to institutes meeting the above criteria from the following countries: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Italy, Norway, Portugal, Romania, Slovakia, Slovenia, Spain Sweden, Switzerland, the Netherlands, Turkey, UK, plus the Institute for Reference Materials and Measurement of the European Commission.

Figure 1 below provides a schematic of call and JRP selection process.

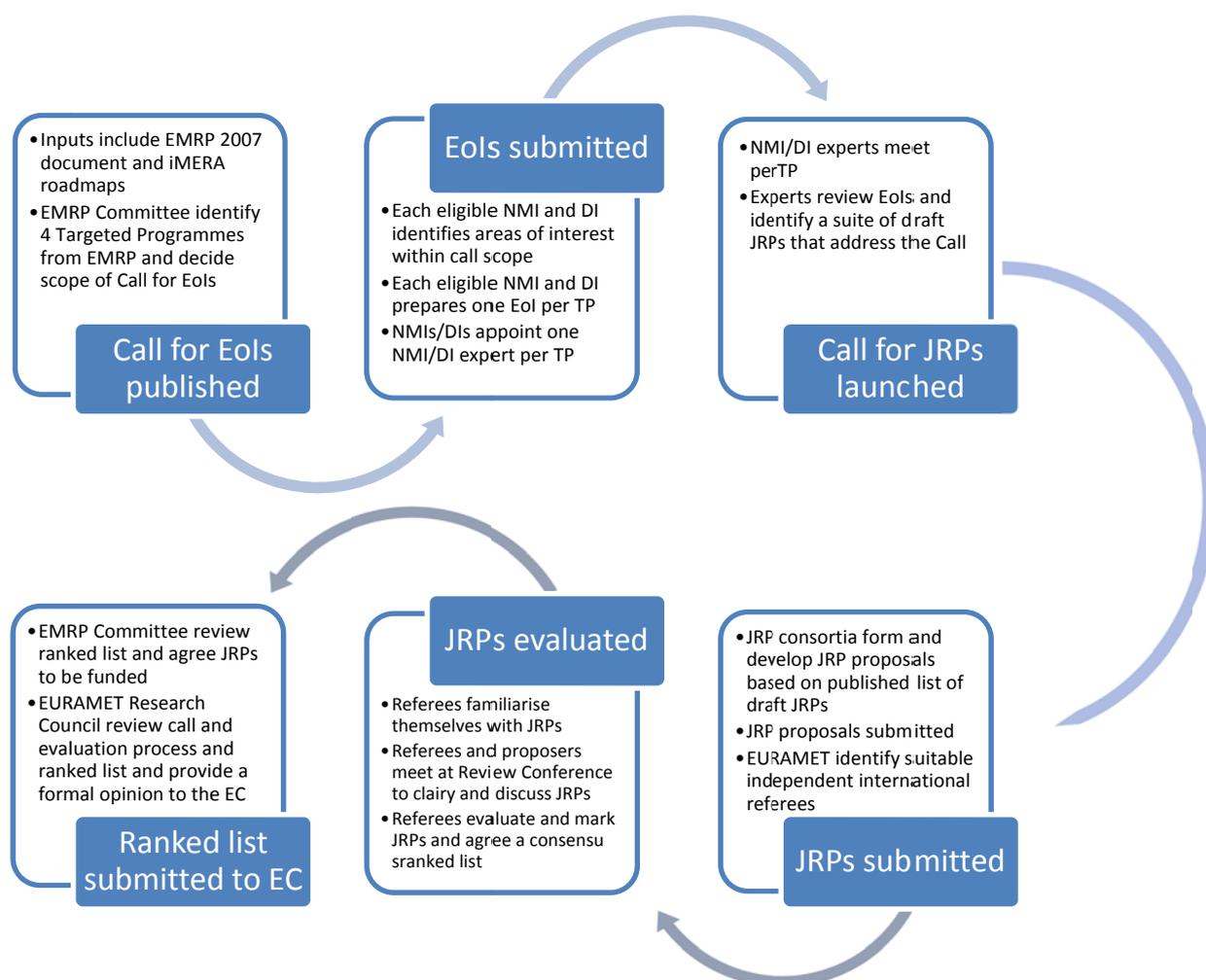


Figure 1: Schematic of call and JRP selection process

The call and JRP selection was operated as a two stage process. The first stage of the Call process, a “Call for Expressions of Interest” was launched at the end of May 2007, with a closing date in early July. This was followed by a second stage in which proposed “Joint Research Projects” – JRPs, were developed with a closing date for submission of 30 September 2007. A helpline and facilitation support was provided to aid proposers through this new process.

Some 98 Expressions of Interest were received by the July deadline from 44 eligible institutes, identifying some 405 Areas of Interest. In the first stage facilitation meetings were held during the summer of 2007 for each of the 4 thematic areas and the NMI experts reduced, prioritised and focussed the research topics such that 39 proposed JRPs were submitted by 30 September 2007 stage 2 deadline requesting 108.25 M€, that is some 171 % of the available budget.

The proposed JRPs were subject to a joint evaluation process by independent international experts selected from outside the European NMI community, culminating in a Review Conference held in Paris in October 2007. The process developed for iMERA-Plus was unusual at European level in that the Referees and the proposers actually meet and discuss the proposed JRPs, enabling clarification and debate, before the Referees formally marked the JRPs and developed their ranked list. Scoring was against 3 key criteria as specified for the ERANET Plus scheme; scientific excellence, quality of the consortia and potential for impact, with a threshold of 3 marks out of 5 in each criteria. Of the 39 proposed JRPs the independent Referees identified 36 as suitable for funding and provided an integrated ranking from the 4 TPs. In practice there was sufficient budget to fund only the 21 highest ranked JRPs.

The final decision regarding the projects to be supported rested with the EMRP Committee, and they endorsed the list as recommended by the independent Referees, without change.

The entire processes and outcome was presented to, and received a strong endorsement from, the EMRP Research Council. The Council includes a balance of representatives drawn from the European and international stakeholder organisations and individual high-level experts drawn from the participating States, including a Nobel laureate and a member of the European Research Council.

The list of selected projects and the opinion of the EMRP Research Council were made available, on schedule, to the Commission before the end of 2007. The list was acknowledged and approved by the Commission on the 18 January 2008. More than 64 M€ R&D funding is committed to the programme of which 21 M€ is provided by the European Commission.

The 21 selected Joint Research Projects were negotiated and contracted during the first half of 2008. Again, EURAMET choose a different approach to that commonly used, with a pair of negotiators travelling to the various coordinating organisations to hold negotiation meetings with the JRP coordinators and other relevant people. The later stages of the negotiation were primarily undertaken by email.

3.2 The Joint Research Projects

The list of the 21 funded Joint Research Projects is shown below in Table 1. All JRPs started between February and July 2008 and were coordinated by 9 different organisations.

JRP Number	JRP Long Name	JRP Short Name	Coordinating Organisation
T1.J1.1	The watt balance route towards a new definition of the kilogram	e-MASS	LNE (France)
T1.J1.2	Avogadro and molar Planck constants for the redefinition of the kilogram	NAH	INRIM (Italy)
T1.J1.3	Foundations for a redefinition of the SI base unit ampere	REUNIAM	PTB (Germany)
T1.J1.4	Determination of the Boltzmann constant for the redefinition of the kelvin	Boltzmann constant	PTB (Germany)
T1.J2.1	Optical clocks for a new definition of the second	OCS	CNRS (France)
T1.J2.3	Candela: Towards quantum-based photon standards	qu-Candela	INRIM (Italy)
T2.J02	Breath analysis as a diagnostic tool for early disease detection	Breath analysis	VSL (the Netherlands)
T2.J04	Metrology on a cellular scale for regenerative medicine	Regenmed	NPL (UK)
T2.J06	Increasing cancer treatment efficacy using 3D brachytherapy	Brachytherapy	ENEA (Italy)
T2.J07	External Beam Cancer Therapy	EBCT	PTB (Germany)
T2.J10	Traceable measurements for biospecies and ion activity in clinical chemistry	TRACEBIOACTIVITY	PTB (Germany)
T2.J11	Traceability of complex biomolecules and biomarkers in diagnostics effecting measurement comparability in clinical medicine	CLINBIOTRACE	LGC (UK)
T3.J1.1	Traceable characterization of nanoparticles	Nanoparticles	NPL (UK)
T3.J1.4	New Traceability Routes for Nanometrology	NANOTRACE	INRIM (Italy)
T3.J2.2	Metrology for New Industrial Measurement Technologies	NIMTech	PTB (Germany)
T3.J3.1	Absolute long distance measurement in air	Long distance	CNAM (France)
T4.J01	Next generation of power and energy measuring techniques	Power & Energy	NPL (UK)
T4.J02	Nanomagnetism and Spintronics	NanoSpin	INRIM (Italy)
T4.J03	Next generation of quantum voltage systems for wide range applications	JOSY	PTB (Germany)

T4.J04	Enabling ultimate metrological Quantum Hall Effect (QHE) devices	ULQHE	LNE (France)
T4.J07	Traceable measurement of field strength and SAR for the Physical Agents Directive	EMF and SAR	PTB (Germany)

Table 1: The 21 funded Joint Research Projects

The 21 Joint Research Projects within iMERA-Plus comprised four themes, SI and fundamental, Metrology for Health, Length and Dimensional Metrology and Electricity and Magnetism Metrology encompassing grand challenges, fundamental science and more SI unit based industrially related research. All selected JRPs required collaborative research to generate the desired impact, and in the vast majority of cases the scope and challenges faced are beyond that which could be effectively addressed by one or two organisations.

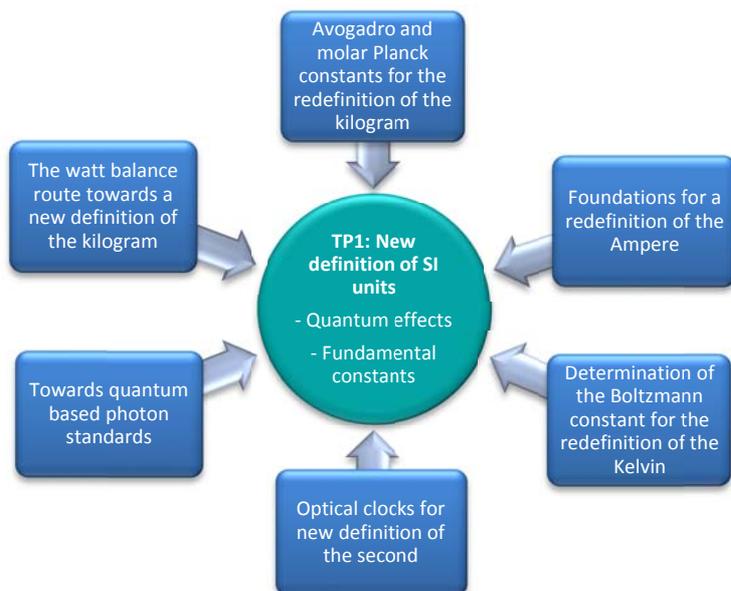


Figure 2: TP SI and Fundamental JRPs

The SI & fundamental projects (see Figure 2) addressed some of the deepest challenges in metrology; providing answers for new standards that push forwards the boundaries in metrology for mass, current and temperature, light down single photon level and time to unimaginable small uncertainty (parts in 10^{17}). These projects helped increase the precision and reliability of measurement at the very highest level, increasing our understanding of the fundamental constants and supporting the redefinition of some of the Units within the International System of measurements.

Metrology projects within the health area (see Figure 3) aimed to underpin new diagnostic tools for early disease detection, increasing our understanding of biomolecules and biomarkers, biospecies and ion activity underpinning clinical chemistry and clinical medicine. They accelerated the exploitation of new regenerative treatments and offered major improvements in the accuracy of external beam and implanted source cancer therapies. Answers were obtained for better measurement of field strength and specific absorbed dose for non-ionising radiation in support of the Physical Agents Directive, protecting workers from harmful electrical fields.

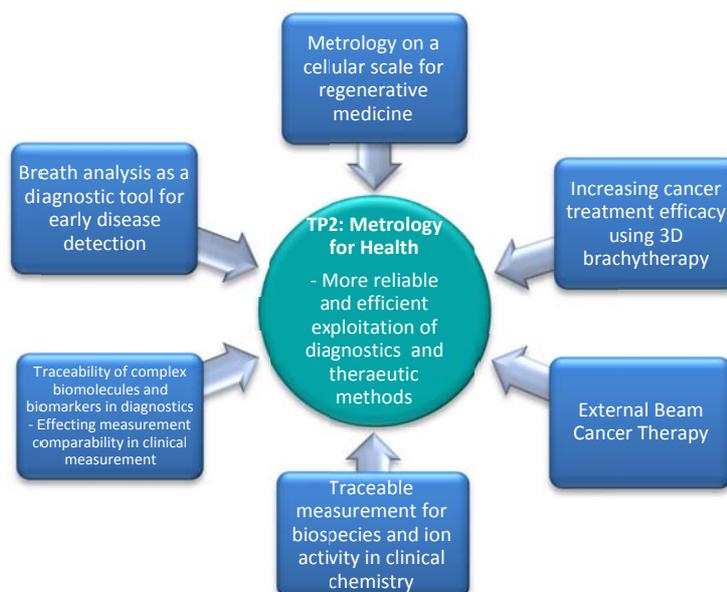


Figure 3: TP Metrology for Health JRPs

The length and dimensional metrology projects (see Figure 4) addressed precise and reliable measurement for nanoparticle characterisation, and developed state-of-the-art traceable

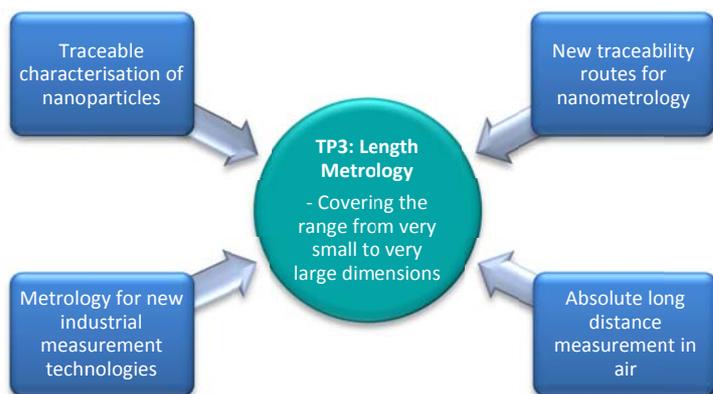


Figure 4: TP Length JRPs

displacement measurements to drive the development of next generation ICT hardware. Moving up in scale, enhanced capability in 3-D metrology will improve the manufacture of large precision objects such as aircraft components. Finally the innovative techniques developed will overcome limitations related to variations in the refractive index of air in precise optical measurement techniques over multi hundred metre distances.

Metrology projects in the electrical and magnetic area (see Figure 5) helped underpin the reliability of power distribution as renewable generation increases its contribution to the grid, and delved deeply into the esoteric world of nanomagnetism and spintronics. Electrical measurements are everywhere and although most people would never be aware of it new or improved quantum standards for AC current and improved Quantum Hall resistance measurements offer rewards far and wide.

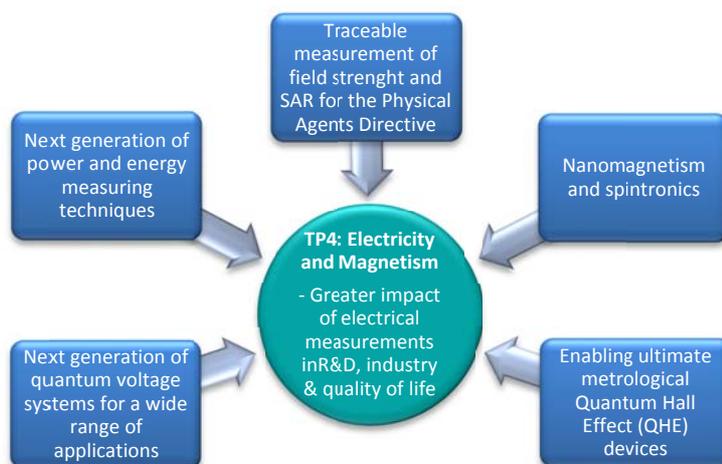


Figure 5: TP Electricity and Magnetism JRPs

3.2.1 e-MASS: The watt balance route towards a new definition of the kilogram

Since the first official adoption of the metric system of units, at the end of the seventeenth century, the concept of natural and universal measurement units underpins all fields of science and engineering. Now, almost all of the base units of the International System of Units (the SI), have been defined by the fundamental constants of physics, except the kilogram, the unit of mass, which is still by definition the mass of the international prototype. This prototype, a cylinder of platinum iridium, is kept safely at the BIPM (International Bureau of Weight and Measures), and plays a central and essential role in the SI. A disadvantage of a unit represented by an artefact is its vulnerability to its environment. The international prototype is suspected to have drifted by several tens of micrograms compared to the various “national copies” disseminated around the world. There is no reason to think that the mass of the international prototype is more stable than the official copies and this is the dilemma of the current realisation of the mass unit.

A promising way of supporting the redefinition of the kilogram is through the watt balance experiment, which links the kilogram to the Planck constant. Two European watt balance experiments are on-going at the National Metrology Institutes in France and Switzerland (since 2002 and 1997 respectively) and this JRP aimed to produce methods and devices to improve these watt balance experiments and support the development of future experiments. Some of the developments were:

- A reduction in the alignment uncertainty within Watt balances, with the project developing mechanical tools to adjust the magnetic circuit induction field horizontality and the watt balance’s coil displacement verticality. Improved position detectors based on propagation properties of laser beams and heterodyne interferometers together with specific collimation methods were also studied to characterise the watt balance’s coil movements. The resulting misalignment uncertainty, modelled for the French watt balance damped suspension was less than 1×10^{-8} .

- The development of noise reduction techniques based on the control of the watt balance's coil velocity; three heterodyne interferometers and sources intended to be operated in a closed loop with piezoelectric actuators were produced. With the aim of improving the scattering of future values of the Planck constant, an *in situ* active compensation device was developed to reduce the disruptive external magnetic field effect on the effective watt balance magnetic field.
- The measurement of the acceleration of gravity with gravimeters based on different principles, such as atomic interferometer or falling corner-cube gravimeters. Three different gravimeters were improved in the project and their uncertainty budget refined. To transfer the gravity acceleration value from the gravimeter to the standard mass of the watt balance, spatial variations were measured and modelled.
- The determination of a value of the Planck constant with a relative uncertainty of 2.9×10^{-7} using the watt balance in Switzerland, which should lead to an even higher accuracy of values of the Planck constant and support the redefinition of the kilogram in the future.

Some of the devices developed during the project can also be used by other scientific and industrial sectors, such as geophysics, inclinometry and position monitoring.

3.2.2 NAH: Avogadro and molar Planck constants for the redefinition of the kilogram

The kilogram is the only SI base unit to be defined by a material object - a Platinum-Iridium cylinder, kept at the Bureau International des Poids et Mesures (BIPM). As a material object is vulnerable to its environment, the cylinder is changing as it ages and therefore a redefinition on the basis of a fundamental physical constant is needed. The objective of this project was to link the mass unit, the kilogram, to the atomic mass unit via the Avogadro constant N_A , which specifies the number of atoms in one mole of substance. The project aimed to demonstrate a direct kilogram realisation based on the mass of a silicon atom (isotope ^{28}Si), expressed in terms of frequency and second. Determining the Avogadro constant in this way involved measurements of the molar mass, volume, surface, density and lattice parameter.

^{28}Si was purified to 99.99 % (natural silicon contains around 92 % ^{28}Si) using centrifuges based at the Central Design Bureau for Machine Building in St Petersburg, Russia. This was then used to grow a crystal that was fashioned into two near-perfect spheres. The enrichment reduced, but did not eliminate, the need to measure the isotopic composition of the crystal, which was performed by means of mass spectrometry and by developing a novel measurement technique based on isotope dilution. Using laser interferometry and synchrotron radiation, each sphere's surface was mapped to measure its volume and to characterise its surface with atomic-scale accuracy. The crystal structure was imaged by x-ray interferometry to measure the atom spacing. The adequacy of crystal perfection and homogeneity to count the silicon atoms on the basis of their ordered arrangement in the crystal was also demonstrated. By calculating the volume taken up by each atom, it was possible to work out how many atoms were in each sphere and, consequently, in a mole, $N_A = 6.02214082(18) \times 10^{23} \text{ mol}^{-1}$. The present measurement uncertainty ($3 \times 10^{-8} N_A$) is 1.5 times higher than that targeted for a kilogram redefinition and is limited by the performance of the measurement apparatus, not by crystal imperfections.

The JRP results will be exploited by the Committee on Data for Science and Technology (CODATA) and the International Committee for Weights and Measures to improve the quality and reliability of data for science and technology and to redefine the SI units on the basis of conventionally agreed values of fundamental physical constants. The ^{28}Si spheres will be used to demonstrate the kilogram based on a fixed value of the Planck constant. The count of the atoms in the spheres provides information on the mass of the sphere. The silicon spheres will also enable the monitoring of the stability of the international prototype kilogram, which is thought to drift by about 50 μg every 100 years. The prototype drift can be measured, or excluded, by mass comparisons between the prototype and a silicon sphere.

3.2.3 REUNIAM: Foundations for a redefinition of the SI base unit ampere

In a proposed redefinition of the international system of units, the ampere and kilogram would be based on fixing values for e (elementary charge) and h (Planck constant). This would replace the 'conventional values' assigned to the Josephson constant (K_J) and the von-Klitzing constant (R_K) in the current system for defining the volt and ohm. In theory there are simple relationships between these four constants ($K_J = 2e/h$ and $R_K = h/e^2$) but these have not been experimentally verified with

sufficient accuracy. The work by metrologists to prove that these simple relationships can be relied upon to define the volt and ohm is an experiment commonly referred to as the Quantum Metrological Triangle (QMT). It requires devices, which generate a known current by counting single electrons. This project aimed to close the QMT and improve the uncertainty associated with e and h values.

Two QMT setups were implemented, based on current and charge comparison. With the charge comparison QMT, a Single Electron Transport (SET) device was operated at an error rate sufficiently low to close the QMT. A precision linkage of the involved 1 pF capacitor to the von-Klitzing constant was performed. This QMT variant was closed with an uncertainty of 1.7 parts per million (ppm). For the QMT based on the current comparison, a cryogenic current comparator was developed which amplified currents by a factor of 20,000. Using the traditional SET devices, evidence was collected that, even in seemingly perfect devices, peculiarities of the transport features may prevent reliable results. This finding has important consequences for the next generation QMT experiments employing high current devices. Progress was made with high current SET devices; hybrid turnstiles featuring a combination of superconducting and normal conducting elements were made and operated in parallel to produce currents of 100 pA and above. The project also developed tunable semiconductor single electron pumps that allow similar or higher currents by higher frequency operation. Finally, an error detection concept was developed which will enable a precise determination of current even when the current generating device operates at error rates as large as 1 in 10^4 .

The results of this JRP will improve the threshold uncertainty (7 parts in 10^7) associated with SI units based on h and e values, through the QMT experiment. The unit of mass, and units derived from it, will also be affected, via the redefinition of the kilogram with the watt balance experiment. The Committee on Data for Science and Technology has confirmed that it will consider the JRP's results in a new report.

The JRP developed three high current SET devices; hybrid turnstiles, tunable semiconductor single electron pumps and an error detection concept to enable the precise determination of current. The high current SET devices have the potential to calibrate current meters with an uncertainty 20 times better than currently available.

3.2.4 Boltzmann constant: Determination of the Boltzmann constant for the redefinition of the kelvin

Since the establishment of the SI units in 1960, extraordinary advances have been made in relating the units to invariant quantities such as the fundamental constants of physics and the properties of atoms.

The present definition of the unit of thermodynamic temperature was adopted by the 10th General Conference on Weights and Measures in 1954, which selected the triple point of water as a fundamental fixed point, thus defining the unit kelvin. However, the development of new primary methods of thermometry that are difficult to link directly to the triple point of water led the Consultative Committee for Thermometry to propose a redefinition of the kelvin using the Boltzmann constant (k). This project aimed to determine the Boltzmann constant, via a number of experimental routes.

In order to reduce the uncertainty in the determination of k , advances have been achieved in the fields of physical acoustics, thermodynamics, microwave measurements, thermometry, dimensional measurements, residual gas analysis, perturbation theory, pressure and capacity measurement, and laser-spectroscopy. The project achieved determinations of k by three methods; acoustic gas thermometry, Doppler broadening thermometry and dielectric constant gas thermometry. All results were consistent with the currently accepted value of k . The standard uncertainty of the project's most recent result corresponded to a reduction in uncertainty by a factor of 1.5.

The results of the project, including the uncertainty budgets, were provided to the interdisciplinary Committee on Data for Science and Technology (CODATA) for evaluation and qualification of the measurements. The outcome of this evaluation should set the standard uncertainty of k at 0.9 ppm, corresponding to a reduction in the uncertainty by a factor of 2. It is anticipated that as a result of the project, the final uncertainty for k will be reduced to a temperature equivalent of $u(k=1) \approx 0.25$ mK, by the time of the redefinition of the kelvin.

The JRP worked closely with the Consultative Committee for Thermometry and its task group on the 'Mise en Pratique for the definition of the kelvin' to help improve temperature measurement. The kelvin can be calculated in two ways, by calibrating a working-standard thermometer against the readings of a primary thermometer or by using the International Temperature Scales. Although the

International Temperature Scales do not rule out methods based on primary thermometry, the lack of their recognition leads to confusion. This JRP helped reduce this confusion by developing International Temperature Scales in the context of other methods.

The JRP fostered the development of a number of primary thermometry methods (e.g. absolute spectral-band radiometry used in steel production) and developed special Johnson noise thermometers, thus benefitting manufacturers of low temperature refrigerators, superconducting magnets and ultra-sensitive sensors.

3.2.5 OCS: Optical clocks for a new definition of the second

Ultra-high performance optical clocks now outperform the best microwave standards based on caesium (Cs) atoms, which are currently used to define the second. A new definition of the second is therefore needed so that it remains based on state-of-the-art technology. The principle underlying the operation of these optical clocks is the use of an optical lattice to freeze the atomic motion. Atoms are strongly confined in a series of potential wells formed by the interference of lasers. By using a large number of atoms simultaneously, this type of clock has superior potential in terms of ultimate frequency stability – presumed to be better than 10^{-18} after one day of integration. The aim of this project was a detailed investigation of a possible optical resonance for the new definition of the second: the $^1S_0 - ^3P_0$ transition of atomic strontium (Sr).

Both the accuracy and stability of optical clocks have been improved in the JRP to a level significantly better than the best Cs fountain primary standards. By using optical resonances as narrow as 3 Hz, corresponding to a quality factor exceeding 10^{14} , and performing the first high performance comparison of Sr lattice clocks, a fractional frequency stability of 5×10^{-17} was demonstrated after one hour of averaging time. The most relevant frequency shifts were studied in detail both experimentally and theoretically. This included the residual effect of the lattice field, the effect of collisions between cold atoms, and the effect of the blackbody field radiated by the environment surrounding the atoms. This resulted in a fractional frequency accuracy of approximately 10^{-16} . Comparisons with a large set of primary standards were performed, resulting in a measurement of the Sr clock frequency in SI units with unprecedented accuracy. Methods were developed for future improvements, such as the demonstration of a non-destructive detection method for the optimisation of the clock frequency stability, as well as technological developments for future transportable or space-bound clocks.

The JRP developed three Sr clocks that can be used as a common reference to repeatedly measure the other clock transitions under investigation at National Metrology Institutes. The project demonstrated the accuracy and stability of these optical clocks and increased knowledge of collisions between cold atoms, atomic motion in the quantum regime and atom-field interactions. The clocks will also be at the heart of two future space missions: ACES/PHARAO and STE-QUEST.

ACES/PHARAO is due to commence in 2014, over 18-36 months, and it aims to demonstrate relative geodesy by mapping the Earth's gravitational field using atomic clocks as sensors of the gravitational redshift. The clocks will be used as references for the evaluation of the gravitational field difference between different locations. Building on the results of ACES/PHARAO, the STE-QUEST project will use a higher level of performance and a different satellite orbit. This mission is scheduled to take place after 2020.

3.2.6 qu-Candela: Candela: Towards quantum-based photon standards

The candela is the SI base unit of luminous intensity; however, its definition is not linked to the concepts of modern physics that underpin the development of quantum optical technologies. A change in optical metrology is therefore required in order to bridge the energy difference between emerging quantum technologies and classical radiometry and photometry, and to connect the measurement of macroscopic quantities such as optical power with the quantum world of the measurement of the number of photons. This project aimed to develop standards for photon metrology from the signal level (10^{13} photons/s – 10^{14} photons/s) of existing radiometric standards ($10 \mu\text{W}$ - $100 \mu\text{W}$) down to single photons. It also aimed to address requirements for new SI traceable quantum based photon standards (in units of photons/ second) and the challenge of expressing the candela in terms of photons per second.

The JRP developed silicon photodetectors with a quantum efficiency predictable with an uncertainty below 10 ppm over the whole visible range of wavelengths and suitable for the measurement of photopic fluxes. It also produced transition edge detectors able to resolve up to 12 photons with an

energy resolution better than 0.12 eV for the measurement of single photon fluxes. Techniques for scaling between low and high photon flux regimes, with uncertainties in the calibration chain of approximately 100 ppm were also developed. These techniques were validated through the Planck constant; by the ratio between the photon flux and the radiant flux of a monochromatic beam at wavelengths of 488 nm, 576 nm and 761 nm at 100 μ W and 761 nm at 1 pW. The JRP demonstrated the validity of expressing the candela in terms of a countable number of photons per second.

The JRP developed new primary standards for the photometry community and a traceability chain based on the most widely used detectors - silicon photodiodes. These new standards are portable, cheaper and easier to use than current standards, making them more accessible to end-users (e.g. National Metrology Institutes and LED manufacturers).

The JRP developed Predictable Quantum Efficient Detectors (PQED) which have been made commercially available by Fitecom Ltd, a Finnish service provider of measuring equipment. The JRP provided validated and traceable standards for the manufacturers of photon counting devices, specifically, spatial uniformity measurements by characterising photon counters. Results showed that candidate channel photomultipliers and single photon counting modules showed poor spatial uniformity results. Publication of this work led to Princeton Lightwave setting up their own spatial uniformity characterisation facility to improve the performance of their diodes.

3.2.7 Breath analysis: Breath analysis as a diagnostic tool for early disease detection

Early disease detection can literally mean the difference between life and death for diseases such as cancer, where the prospects of curing patients are significantly higher following early diagnosis. Breath analysis is a non-invasive method for monitoring the volatile organic compounds present in an individual's exhaled breath and is one of the clinical tests that can be used for early disease detection. Recent advancements in laser absorption spectroscopy techniques have led to the development of small, calibration-free devices for performing breath analysis tests, with time-resolved measurements. However, despite these advancements, the accuracy and reliability of breath analysis measurements still requires considerable improvement. This project addressed these measurement issues with the aim of producing reliable identification and quantification of selected compounds present in exhaled breath.

The JRP demonstrated that measurements of methane, carbon monoxide and carbon dioxide can be performed with an expanded uncertainty of 1 % - 2 % with detection limits down to amount-of-substance fractions of 1 nmol mol⁻¹ or better. This level of uncertainty is negligible in comparison with the natural variations in amount of these components in human breath. For other targeted molecules, such as methanol, ethanol, acetone, formaldehyde and ammonia, the uncertainty ranges between 3 % - 5 %, because of adsorption effects in gas sampling systems. For the above listed molecules, reference data has been obtained and compared to spectroscopic databases, which are used as a basis to convert spectroscopic data into gas composition data. For ethane and formaldehyde it was found that the most widely used database HITRAN was incomplete and several tabulated line strengths had an error of more than 10 %. Methods and protocols were also developed for applying various spectroscopic techniques in breath analysis. One protocol linked laser-based spectrometric principles to metrological aspects of breath analysis and explained how equipment should be calibrated in order to obtain traceable measurements from spectroscopic reference data. Experiments with moisture removal from gas mixtures demonstrated the versatility of these techniques and enabled the quantification of errors introduced by sample preparation.

The JRP successfully demonstrated the potential application of spectroscopic techniques in the medical field. The techniques and methods developed have resulted in improved measurement quality for medical trials, leading to reduced repetition of measurements and an improved basis for combining the results from different trials.

Virtually anyone who uses spectroscopic techniques uses databases such as HITRAN and PNNL in order to convert spectroscopic measurement data into gas compositions. The accuracy of the gas composition derived depends on the accuracy of the gas mixtures used for obtaining these reference data. The project showed that the HITRAN database was incomplete for ethane and formaldehyde and several line strengths had an error of more than 10 %. By supporting the improvement of these databases the project benefited end-users in spectroscopic gas analysis, including those outside of medical breath analysis e.g. the certification of reference materials for specialty gas manufacturers and purity analysis.

3.2.8 Regenmed: Metrology on a cellular scale for regenerative medicine

With an increasingly ageing population there will be times when we will all require some form of healthcare support in order to manage disease and maintain our quality of life. However, the challenge for healthcare providers and governments is to manage these potentially spiralling health costs. Significant savings could be made through tissue regeneration; growing new cells to replace damaged or diseased tissue, thereby removing the need for long-term drug treatment and the possibility of adverse side effects. This project aimed to support regenerative medicine by developing robust procedures for cell growth measurement and characterisation, and by defining cost effective metrics for assessing the consistency of products containing living cells.

Techniques such as CARS (Coherent Anti-stokes Raman Spectroscopy) and MALDI (Matrix-Assisted Laser Desorption/Ionization Imaging) spectrometry were developed for use in characterising the behaviour of cells in regenerative medicine products, thus providing support for the regulation of these products. The JRP developed specialised methods to understand the measurement uncertainty associated with diagnostic evaluation of cells in clinical samples, thus helping the healthcare sector to make more reliable diagnosis. The measurement science developed in this project is being used to support work in specialised centres in Europe, such as through dissemination activities organised by the Fraunhofer Institute (e.g. The World Congress on Regenerative Medicine), and by direct links with technology innovation centres. The JRP also developed measurement techniques to ensure products are safe and well characterised when used in humans, thus supporting the social acceptance of the new field of regenerative medicine products.

The JRP developed measurement technologies and methodologies that enable European companies to meet the requirements for cell characterisation, as defined in the Advanced Therapy Medicinal Product Directive 2009/120/EC. They have also input into standardisation bodies; ISO Technical Committee 150 - *Implants for surgery*, ASTM International Committee F04 - *Medical & Surgical Materials & Devices* and BSI Committee RGM/1 - *Regenerative Medicine*.

The JRP enabled project partners to act as a virtual 'Centre of Excellence' for regenerative medicine and the characterisation of cell containing products. The project has also provided stakeholders with access to cutting edge measurement technology such as Two-Photon Excitation Fluorescence Microscopy, CARS, MALDI and Desorption Electrospray Ionization (DESI) Mass-Spectrometry.

The JRP;

- Supported medical companies in the development of new biomaterial surfaces that cells can easily adhere to, using traditional textile technologies
- Helped cell therapy companies to develop cell characterisation techniques that do not rely on animal testing
- Enabled spectroscopic techniques (developed for studying cell culture biomarker molecules) to be applied in the detection of counterfeit medicines
- Allowed companies using fluorescent biomarkers to obtain reliable results and to have more confidence in their analysis.

3.2.9 Brachytherapy: Increasing cancer treatment efficacy using 3D brachytherapy

Brachytherapy is a cancer radiotherapy approach where small, sealed radioactive sources are placed inside, or in close proximity to, the area requiring treatment. It is commonly used to treat cervical, prostate, breast and skin cancer and can be used alone or in combination with other therapies. In Europe, approximately 100,000 patients per year are treated using brachytherapy, but in order to optimise cancer treatment and satisfy the recommendations of the International Atomic Energy Agency (IAEA) TRS-398 2000, an improvement in the accuracy of brachytherapy dosimetry is required. This project aimed to address this issue by establishing traceable measurements of brachytherapy radiation sources using absorbed dose to water (D_w) primary standards. These new D_w standards developed should simplify existing measurements and reduce dose uncertainty to below 5 %, at the clinical level.

A number of primary standards were designed and built for measurements of D_w imparted by brachytherapy sources using low dose-rate (LDR) or high dose-rate (HDR) regimens. For LDR dosimetry, three standards were established by participating National Metrology Institutes, based on ionometric methods. For HDR dosimetry, two primary standards based on water calorimetry were developed along with two other HDR standards based on graphite calorimetry. The project developed

a calibration chain optimised to transfer the new reference quantity D_w to end-users. In particular, a measurement procedure was developed for selected models of well-type chambers. In order to select the models of well-type chambers a questionnaire was distributed to irradiation facilities using brachytherapy dosimetry at secondary standards laboratories and medical centres in Europe - 137 centres responded from 9 different countries. To support the link between the current metrology (air kerma standards) and the new D_w standards, the dose rate constant (λ) was re-evaluated for all brachytherapy sources used within the project. The project also developed suitable portable methods to improve the verification of the 3D dose distributions of brachytherapy sources in water or in water equivalent phantoms.

The JRP results have input into an AFNOR working group, which is a mirror of ISO TC 85/SC2 WG22 '*Dosimetry and related protocols in medical applications of ionizing radiation*' and have fed into the revision of DIN standard 6809-2 '*Clinical dosimetry; Brachytherapy with sealed gamma sources*'. The results of the JRP were presented to the IAEA, where the move from air kerma to D_w standards for dosimetry for brachytherapy was discussed with the support of the medical community. The JRP also has the support of, and has benefited from input from, the European Society for Radiotherapy and Oncology.

3.2.10 EBCT: External Beam Cancer Therapy

Approximately 1.3 million people will die due to cancer in Europe in 2011. Therefore, a way to improve patient treatment and increase survival is urgently needed. This project aimed to improve dosimetry for high-intensity therapeutic ultrasound (HITU) and modern ionising beam radiotherapies. Therapies such as Intensity Modulated Radiation Therapy (IMRT) can be used to provide a more conformal dose distribution than conventional radiotherapy, thereby increasing the dose of radiotherapy to tumours, while sparing healthy tissue. However, to support the use of HITU further knowledge of the temperature of the 'dose' and its distribution during administration is required. In addition, both HITU and IMRT techniques pose a challenge for dosimetry, due to the small size of the radiation field. The International Commission on Radiation Units states that the applied dose should have an uncertainty of less than 2.5 %, but to achieve this, both the radiation and field size need to be precisely quantified.

Technical achievements from the project included:

- **Dosimetry in small fields:** The measurand absorbed dose to water, (D_w) was measured using a graphite calorimeter and a water calorimeter with beam qualities 6 MVX, 10 MVX and 12 MVX with field sizes of 10 cm x 10 cm down to 3 cm x 3 cm. The uncertainties obtained were as low as 0.3 %. The calibration coefficients of ion chambers and the responses of alanine dosimeters determined in these fields showed no dependence on the field size within the limits of the uncertainty. Using Monte-Carlo simulations, the response of alanine was extrapolated for smaller fields (1 cm x 1 cm). No significant size dependence was found within the uncertainties. A diamond detector, developed in co-operation with the Roma Tre University, Italy, was used for measurements in the fields 1 cm x 1 cm, 6 MVX and 10 MVX in comparison with alanine, and demonstrated uncertainties of less than 1 %.
- **Dosimetry for hadron therapy:** Measurements were performed successfully at GSI: The Centre for Heavy Ion Research in Darmstadt to demonstrate D_w in a ^{12}C -beam with 280 MeV/u. The calibration coefficients of ion chambers were determined and were in agreement with the uncertainties given in the International Atomic Energy Agency (IAEA) report TRS 398.
- **HITU:** Improved sensors for measuring spatial pressure distributions and total acoustic output power of HITU transducers were developed with the aim of determining the temperature applied with a higher accuracy. The first inter-laboratory comparison of HITU power measurement methods was successfully carried out.

The beam quality correction factors (k_Q factors) developed by the JRP are being incorporated into an update of the German standard DIN 6800-2 '*Procedures of dosimetry with probe type detectors for photon and electron radiation - Part 2*'. The k_Q factors will also be incorporated in a future version of the IAEA report TRS 398 '*Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water*'.

The results of the JRP have supported two national dose verification studies for IMRT. In Belgium the quality assurance study BELdART involved virtually all Belgian therapy centres. Whilst in the UK, a national audit was performed by the National Health Service and NPL, the UK's National Metrology Institute, between June 2009 and March 2010. The aim of both studies was to provide an independent check of IMRT delivery.

The JRP validated the use of alternative detectors, such as alanine and diamond detectors, as standards for IMRT. This offers new possibilities for calibration in situations where ion chambers cannot be used.

3.2.11 TRACEBIOACTIVITY: Traceable measurements for biospecies and ion activity in clinical chemistry

Traceable and comparable measurements in clinical chemistry are a mandatory requirement of EU legislation (In Vitro Diagnostic Medical Devices 'IVD' - Directive 98/79/EC). However, the measurement of biospecies in blood serum is currently restricted to the determination of their total amount, although it is well understood that a 'clinical' effect often depends on the identity and quantity of biospecies or ion activities rather than the total amount. What is required is the ability to identify and quantify biospecies and measure ion activity in clinical samples. This is particularly important for calcium, one of the most frequently measured analytes in clinical chemistry, and heteroatom-containing drugs (e.g. sulphur and selenium metabolites), which are used to sensitise cancer cells to chemotherapy. This project aimed to provide internationally accepted reference points to calibrate new and existing measurement systems in the medical diagnostic field.

Reference methodology for the accurate trace measurement and identification of toxic and essential heteroatom containing species in human serum was developed, with selenomethionine (SeMet) and methyl-Se-cysteine selected as target analytes. ⁷⁶Se-enriched SeMet was produced and characterised as a labelled spike, which was then used for species-specific isotope-dilution mass spectrometry method development. Enzymatic and acid hydrolysis procedures were also developed to extract and quantify SeMet from albumin. A largely accelerated extraction procedure was achieved by microwave-assisted extraction without compromising SeMet extraction efficiency.

A system for the SI traceable measurement of the ionic species activity in physiological matrices was developed, which focused on sodium, potassium, chlorine, magnesium and calcium ions. High purity materials were characterised at a primary level and subsequently used to prepare gravimetric mixtures as calibration standards. The unknown activities, the free biological active part of the compounds in these mixtures, were calculated based on established model calculations. Measurement systems as well as measurement methods including defined procedures for signal acquisitions and data evaluation were developed in order to quantify the ion activity and measurement uncertainty. The conductivity of highly purified water is an indispensable reference point for activity measurements and quality control parameters for pharmaceutical purposes and an experimental set-up for low range conductivity of highly purified water at a primary level was established.

The methods developed in the JRP have been used in an on-going European Clinical Trial *Selenium and Prostate Cancer: Clinical Trial on Availability to Prostate Tissue and Effects on Gene Expression*. The study is run by Wageningen University, the Netherlands, and is a double-blind, randomised, placebo-controlled intervention trial aimed at examining the effects of selenium supplementation. The trial examines the relationship between dietary selenium intake and changes in gene expression profiles that might be responsible for selenium-induced chemoprevention. Measurement methods for SeMet in human serum have been validated by an international intercomparison (EURAMET TC-MC project 1165), which included National Metrology Institutes and expert laboratories (e.g. NIMT Thailand, CCS Switzerland, DIMCI/DQUIM Brazil).

The JRP submitted new measurement procedures for ion activity to the Joint Committee for Traceability in Laboratory Medicine (JCTLM).

3.2.12 CLINBIOTRACE: Traceability of complex biomolecules and biomarkers in diagnostics effecting measurement comparability in clinical medicine

The International Federation of Clinical Chemists (IFCC) and the Joint Committee for Traceability in Laboratory Medicine (JCTLM) have highlighted the need to develop reference measurement systems to provide traceable values for complex biomolecules, such as disease state protein biomarkers. This should also enable in vitro diagnostic (IVD) and clinical measurement comparability and improve

diagnostic efficiency and reliability. However, few reference measurement procedures exist for protein biomarkers and biomolecular measurements and consequently standards can be affected by multiple parameters that need to be considered in the establishment of a traceability chain. The critical measurement is not the total amount of a protein biomarker but the quantity of 'active/functional' component. A protein's structure, folding state and interactions with other proteins/ligands all define its activity and can influence the measurement result and its diagnostic 'clinical' value. This project aimed to address these issues by developing measurement procedures for complex protein biomarkers in order to provide SI traceable results.

The JRP's most significant achievement was the successful demonstration of the feasibility of developing reference measurements, that deliver SI traceable values and reference materials for two clinically important biomarkers; human growth hormone (hGH) and C-reactive protein (CRP). The project developed, validated and published strategies for the application of isotope dilution mass spectrometry (IDMS) methods for the quantification of hGH and CRP in purified materials and serum matrixes. Robust and selective enzymatic digestion and cleanup protocols were developed enabling assignment of SI traceable values for hGH in serum by IDMS using isotopically enriched peptides and proteins as internal standards. Method development and optimisation for isoform profiling and quantification of oligomeric and aggregation state which has influenced immunoactivity in hGH and CRP reference preparations was also undertaken.

The JRP evaluated advanced mass spectrometry-based techniques for the elucidation of protein structure:

- Hydrogen Deuterium Exchange (HDX) in combination with proteolysis mass spectroscopy and Ion Mobility Mass Spectroscopy (IMS) were optimised to assess structural differences in the currently available reference standards for hGH
- The potential for HDX and IMS for quantification of protein folding states and protein ligand interaction was demonstrated
- The significant influence of sample preparation, heterogeneous isoforms and structures on clinical immunoassay response for both hGH and CRP was demonstrated

The World Health Organization (WHO) has expressed an interest in the project's multiparametric protein quantification providing SI traceable values for value assignment of relevant WHO International Standards for biologicals. Project results may be acknowledged in future revisions of ISO TC212 '*Clinical laboratory testing and in vitro diagnostic test systems*' documentary standards.

The JRP engaged with key clinical and metrology stakeholders, including the IFCC, JCTLM and Consultative Committee for Amount of Substance (CCQM) BioAnalysis working group. The JRP-Partners participated in the IFCC Scientific Division, IFCC hGH and plasma proteins working groups. The results of the project have input into IFCC guidance, clinical test kits and the organisation of clinical commutability studies.

The IDMS method developed for protein quantification is currently being used by National Metrology Institutes following dissemination through a CCQM study. JRP has also provided guidance on key parameters identified as influencing immunoassay responses to IVD manufacturers, reference material producers and external quality assurance organisers.

3.2.13 Nanoparticles: Traceable characterization of nanoparticles

Nanoparticles have many applications, e.g. in suspensions in the ink industry, in drug delivery or as diagnostic agents for the pharmaceutical industry and in novel composite materials to improve properties such as strength and electrical conductivity. However, at the start of this JRP, there were no formally recognised, traceable calibration standards and only one European National Metrology Institute could measure the size of spherical nanoparticles. This project aimed to provide traceable calibration of nanoparticles smaller than 100 nm with an accuracy better than 1 nm. It focused on nanoparticle sample preparation, traceable measurement of spherical nanoparticles and high aspect ratio nanoparticles.

This project established dimensional traceability for a range of nanoparticle measurement techniques:

- Scanning Probe Microscopy (SPM)
- Scanning Transmission Electron Microscopy (STEM)
- Transmission Electron Microscopy (TEM)

- Scanning Electron Microscopy (SEM)
- Dynamic Light Scattering (DLS)
- Small Angle X-ray Scattering (SAXS)

The JRP identified artefacts for these techniques and conducted inter-laboratory comparisons of particle size measurements. The results demonstrated an uncertainty of less than 1 nm. A new prototype instrument for aerosol particle measurement was also produced and validated: SCAR (Single Charge Aerosol Reference), which produces singly charged particles in a wide particle size range.

The JRP contributed to the first European Reference materials for Nanoparticles. To achieve this, four of the JRP-Partners participated in a validation exercise for nanoparticle measurement techniques (i.e. DLS, STEM, SPM, SEM, and SAXS). The JRP results have fed into two international standard committees *ISO TC229 Nanotechnologies* and *ISO TC24 Particle characterisation including sieving*. The JRP also prepared a Good Practice Guide on the accurate measurement of spherical nanoparticles, to enable end-users to set up and carry out measurement of nanoparticles with minimal uncertainty.

3.2.14 NANOTRACE: New Traceability Routes for Nanometrology

As nanotechnologies and ICT (Information and Communication Technologies) play increasingly crucial roles in modern life, the demand for increased accuracy of dimensional measurements is growing rapidly, for example due to miniaturisation of components and structures. One example is in semiconductor manufacturing, where laser interferometers are currently the essential measurement tool. The increased use of double-patterning techniques with a reproducibility of about 0.3 nm for mask metrology tools requires more accurate techniques than are currently available. This project aimed to achieve a 10 pm accuracy for displacement metrology by developing and refining next generation optical interferometers. The challenge was to reduce the uncertainties by one order of magnitude with respect to the current state-of-the-art.

The JRP produced six high-resolution interferometers, based on the different techniques developed in the JRP: including a cost-effective method that uses combined capacitive distance sensors for modelling and correction of interferometer nonlinearity with 10 pm accuracy. The performance of five of these optical interferometers has been verified using the NPL x-ray interferometry facility which was redesigned and refined. A differential Fabry–Pérot interferometer, used for ultra-small angle measurements, was also produced. Both the x-ray interferometer and the Fabry–Pérot interferometer have supported the work of the JRP NAH, where they were used to accurately measure the lattice constant and determine the shape of the ^{28}Si sphere, respectively. Guidelines on the use of interferometers for traceability at the nanoscale, based on the experience gained within the project, are available for researchers on the Nanotrace website.

The JRP produced a phasemeter and interferometer that will be used to improve the line scale comparator at PTB, Germany's National Metrology Institute, by reducing measurement uncertainty and short periodic errors to below 0.1 nm. The phasemeter will also be used to improve the speed and accuracy of Atomic Force Microscopes and Scanning Electron Microscopes for the determination of line width, form and fluctuation, where the required accuracy is below 0.1 nm. The x-ray interferometry facility will be available for measuring errors in optical interferometers and will be used to characterise instruments used in the semiconductor industry.

The JRP produced a new transfer standard (transportable actuator), which will be used for the validation of accurate displacement sensors such as interferometric, confocal and capacitive sensors, used in industrial measurements and for fundamental research.

The JRP collaborated with optical component manufacturers (MCSE, France and SILO, Italy) and micro displacement actuator manufacturers (Physik Instrumente, Germany, Mad City Lab Inc., USA and Queensgate Instruments, UK) and identified how to improve and support their manufacturing processes.

3.2.15 NIMTech: Metrology for New Industrial Measurement Technologies

Engineering designs for products such as aircraft and cars are becoming ever more sophisticated with aerodynamic considerations and efficiency savings at the forefront of manufacturer's concerns. While designs become more complex, manufacturing tolerances become smaller and capabilities often fall short of what is required to meet the vision of designers, meaning that what works in theory is

sometimes harder to realise in practice. The lack of traceable large-scale measurements and freeform surface characterisation are two obstacles which prevent manufacturers from testing exactly what rolls off their assembly line to a suitable degree of traceability, whether it be a section of an aircraft wing, a wind turbine blade or the body panel of a family saloon car.

Although Coordinate Measurement Machines (CMMs) are capable of making traceable measurements using both optical and tactile techniques, the development of portable optical systems is vital, especially in industries where heavy, bulky machines are impractical and a portable laser tracker system, for example, may be better suited to the measurement task. It is not practical to measure the entire wing of a large aircraft, even with a large CMM, so the possibility of taking the measuring instrument to what needs to be measured, and carrying out a traceable measurement in situ, is a huge step forward.

Three main challenges in large-scale dimensional measurements prevent manufacturers from testing exactly what rolls off their assembly lines include:

- a lack of calibrated measurement standards
- inadequate measuring techniques to implement task-specific measurement uncertainty of large parts directly on the shop floor
- a lack of internet infrastructure for online validation of Coordinate-Measuring Machine (CMM) evaluation software and other geometrical evaluation algorithms

This JRP aimed to improve the understanding of large scale dimensional measurements by developing new and traceable measurement technologies – different advanced measurement standards, sophisticated measuring techniques, and good practice guides on the use of indoor GPS, laser-tracers and other mobile measuring technologies.

The JRP developed innovative and advanced standards designated for traceable measurements, calibration of parts, and performance assessments of measuring systems including:

- A new multi-lateration measuring system (M3D3) dedicated to the measurement of large objects has been developed and validated. This novel system can implement task specific uncertainty measurements and map CMM error, and can also be retrofitted into either a laboratory or industrial shop floor. The M3D3 is currently housed at PTB, Germany's National Metrology Institute, and will be used by manufacturers of large-scale parts, the automobile industry, the aerospace industry and other CMM users.
- Tetrahedron standards with ceramic optically cooperative targets for CMMs
- A new software validation technique has been developed; the Internet Aided Software Validation (IASV) infrastructure enables clients to communicate online for the purpose of CMM software and other algorithm validation.
- A new method for verifying the performance of laser trackers was developed that not only improves the available diagnostic information it also reduces the verification time from 6-8 hours to 1 hour. This coupled with the fact it can be implemented as an onsite test in most production environments greatly reduces downtime leads to cost savings.
- A large involute gear standard with a diameter of 1 metre to assist industries in assessing the performance of large-scale measurement machines, the implementation of task specific uncertainty measurement and the accurate measurement of complex parts.
- A waviness standard to assist the automobile industry
- Comprehensive good practice guides and software for error detection and configuration of multi-sensor measurement systems that will be used by developers and users of multi-sensor networks, aircraft and automobile manufacturers, machine tool industries and calibration laboratories.
- Launching a pilot Internet Aided Software Validation (IASV) infrastructure that is currently being tested by eight industrial partners: Carl Zeiss Industrielle Messtechnik GmbH, Klingelnberg GmbH, Mahr OKM GmbH, Messtechnik Wetzlar GmbH, Mitutoyo Messgeräte GmbH CTL, Mahr OKM GmbH, FRENCO GmbH, PTB Berlin.

3.2.16 Long distance: Absolute long distance measurement in air

Large scale production, in particular in aerospace, global monitoring (geodesy) and waste management, all require the measurement of dimensions to levels of accuracy currently unachievable

over long distances (over 10 m). To date, the best instrument for long range distance measurement achieved an accuracy of approximately 5×10^{-7} when atmospheric parameters were sufficiently stable – but this instrument is no longer commercially available and required highly skilled operators.

This JRP aimed to improve the current state of the art in long range distance measurements in air to produce a relative accuracy of 10^{-7} . It also aimed to improve current techniques for the measurement of air refractive indices and develop and refine synthetic wavelength interferometers.

Spectroscopic sensors were built, enabling measurement of temperature and humidity along a given optical path. A resolution of 10 mK and an uncertainty better than 0.1 K was demonstrated for temperature measurement. An improvement of air index compensation compared to a classical thermometer was also demonstrated and relative humidity was measured with an uncertainty of less than 4 %. The spectroscopic sensors were used successfully outdoors up to 72 m for humidity and up to 200 m for temperature. Three new types of transportable telemeters were produced; two based on synthetic wavelength interferometry and one on time of flight techniques using femtosecond lasers. The best resolution obtained with synthetic wavelength interferometry systems was less than 1 mm with an uncertainty of less than 10 mm indoors for absolute measurement. Similar results were found with time of flight techniques up to 100 m. Pulse to pulse interferometry was implemented for distance measurements up to 50 m (100 m propagation through air). A comparison with laser interferometry demonstrated measurement agreement within 2 mm for this distance (4×10^{-8} uncertainty). Dispersive interferometry methods were also compared and showed measurement agreement within 0.5 mm at 50 m (relative uncertainty $<10^{-8}$) compared to the counting laser interferometer.

The JRP developed:

- a transportable spectroscopic thermometer
- transportable spectroscopic hygrometers
- a transportable distance metre with no air index compensation for indoor and outdoor application
- a transportable distance metre with air index compensation
- a distance metre based on femtosecond lasers for indoor application
- a distance meter based on femtosecond lasers for indoor and outdoor application

After further advancement to make them more compact and robust, these prototypes could support the metrological, geodesic and surveying communities.

The prototype spectroscopic thermometer has been used in the development of a commercial oxygen analyser by Gaset Technologies Inc.

The JRP produced guidelines for the use of the new techniques and prototypes for measuring absolute distances, which will be available to all interested stakeholders and long distance measurement end-users.

3.2.17 Power & Energy: Next generation of power and energy measuring techniques

Europe faces potential energy shortages as fossil fuel supplies diminish and nuclear power facilities age, but there is also pressure to reduce greenhouse gas emissions and a commercial demand for an electricity supply of the highest quality - free from momentary voltage interruptions and interference. Sustainable energy sources such as wind and solar energy are becoming more and more available however, coupling wind and solar plants to the electricity network causes several technological challenges. Firstly, energy production becomes less and less centralised, rendering the electricity network increasingly complex. Secondly, such plants generate all kinds of higher harmonics, which may lead to additional energy losses, power failure or even damage to equipment. These challenges are a catalyst for new technologies that require a new generation of power and energy measurements, made directly at generation and distribution sites and involving the accurate measurement and analysis of complex wave shapes.

This project aimed to develop new instruments, algorithms and methodologies to make these required measurements to support an EU regulatory framework that oversees the market for electrical goods and power generation.

The high current and high voltage levels that are prevalent at electricity distribution/generation sites were accurately transformed to lower measureable levels. This entailed the development and

characterisation of lab-use and portable transducers to cover a wide range of currents and voltages up to 33 kV. These transducers can be connected to the electricity system without interrupting the supply. Having transformed the signal levels, the electrical measurement and computer processing of the AC waveforms was made possible by digitising the signals using six channel analogue to digital convertors that operated at high data output rates continuously converting the waveform with known fidelity. The resulting data was processed using algorithms, producing the complex range of power quality metrics used by industry. The waveforms of interest are continuously changing as the electricity demand changes requiring the development of new waveform transforms to analyse these complex waveforms.

The JRP developed techniques to reduce errors in conformance testing to help protect the multi billion euro electrical goods industry. This will also help to protect the electricity network from exposure to sub-standard equipment.

New services to calibrate instruments were developed using the technology, protocol methodology and guidelines developed in the project. The new services will be offered to end-users by project partners.

The JRP also undertook seven successful on-site tests of medium voltage networks (33 kV), high current measurements (kA), power loss measurements in network transformers and power quality at distribution substations in the UK, Finland, Italy and Sweden.

3.2.18 NanoSpin: Nanomagnetism and Spintronics

Developments in the fields of nanomagnetism and spintronics include a wide range of applications such as ultra-strong magnets, spin polarized materials, ultra-high density recording media (hard discs, flash memories/MRAM), spin transistors and DNA- and bio-sensors. All of these developments urgently require measurement tools to reliably and traceably characterise magnetic nanomaterials. The aim of this project was to establish a metrological basis for the field of nanomagnetism and to provide reference samples and measurement methods to industrial and academic end-users.

The project produced a number of reference nanomaterials including thin films of Permalloy integrated in coplanar waveguides for time and frequency domain dynamics measurements, Gallium Manganese Arsenide (GaMnAs) diluted magnetic semiconductor samples for precessional dynamics, size monodispersed nanoparticles for high resolution scanning probe microscopy and ultra-sensitive magnetic moment detection and samples of hard magnetic materials with perpendicular anisotropy for high resolution scanning probe microscopy.

The project developed the inductive metrology of ferromagnetic resonance frequency (fFMR) and the Gilbert damping of soft magnetic thin film was established and validated and a set of calibrated soft magnetic reference samples is available for external inductive measurements of fFMR and alpha. Metrology for the Spin Torque precession of individual nanodevices in time and frequency domains was also established.

Quantitative Magnetic Force Microscopy with a resolution of less than 50 nm was demonstrated using magnetic nanoparticles. A prototype magnetic detector based on nano-SQUID magnetic moment sensitivity and a nanosized (<500 nm) metallic and semiconductor (i.e. two dimensional electron gas heterostructures) Hall sensors were developed.

New reference samples and techniques were developed and transferred to industrial and academic end-users, such as: time resolved damping techniques (used by Singulus Technologies AG and University of Bielefeld, Germany), damping reference samples (used by Tohoku University, Japan), nano-SQUID detection technique of a single nanoparticles (used by University of Tübingen, Germany), and Hall sensor detection techniques for single nanoparticles/ nanowires (used by University of Duisburg, Germany and CSIC, Spain).

A 'Nanomagnetism' group, involved in a wide range of scientific activities and their dissemination, was created with JRP collaborators, and included reference nanomaterials (University of Duisburg, Trinity College Dublin, University College Cork, University of Vienna), sensor fabrication and nanomanipulation (Imperial College London, Cambridge University, Surrey University), preparation of hard magnetic thin films for hard magnetic reference samples (TU Chemnitz, Hitachi and IMEM Parma), ferromagnetic resonance and damping for microwave applications (Tohoku University, NIST Boulder, University of Colorado, Northeastern University Boston), tunnelling magnetic junctions dynamics and point contacts for memory/sensor applications (Singulus AG, University of Bielefeld,

NIST Boulder) and high resolution magnetic microscopy/MFM calibration (TU Chemnitz, Hitachi GST, University of Parma, University of Göttingen, IFW Dresden, TU Braunschweig, Magnicon GmbH).

3.2.19 JOSY: Next generation of quantum voltage systems for wide range applications

The use of microelectronic circuits in control systems in commercial devices is constantly increasing and is improving the performance and efficiency of mass-produced items. However, the performance of a control system depends on the performance of electronic components (e.g. analogue to digital converters [ADCs] and digital to analogue converters [DACs]), and the performance of the components, in turn, depends on the performance of the electronic measurement equipment used to test them. This project aimed to introduce quantum-based measurement systems into AC metrology, providing faster calibrations with lower uncertainties with the aim of supporting electronic measurement and test equipment used in research and development.

The JRP extended the application area for Josephson based methods and produced much better Josephson Synthesizers (JoSys) and quantum-based voltage measurement systems. A new technology based on a more robust barrier material, $\text{Nb}_x\text{Si}_{1-x}$, will form a new basis for Josephson array fabrication. The first wafers containing binary-divided 10-V Josephson series arrays, fabricated for 70 GHz operation and consisting of about 70,000 junctions, demonstrated a good yield and wide constant voltage steps with a width of around 1 mA. A Josephson voltage standard locked synthesizer (JoLoS) has been developed. The JoLoS with amplitude feedback can be used as a source to drive low impedance with an uncertainty below $1.5 \mu\text{V/V}$, ranging from 100 mV to 1 V and 10 Hz to 1 kHz. Differential sampling methods in thermal converter measurements achieved uncertainties below $0.1 \mu\text{V/V}$ for frequencies up to 100 Hz. A flexible Josephson two-terminal-pair bridge method was developed and demonstrated uncertainties of a few parts in 10^8 at 10 k Ω , comparable to those of conventional impedance bridges. The Josephson bridge can measure over a much wider frequency range, from 25 Hz up to 10 kHz and over a wider range of impedance ratios than conventional two-terminal-pair bridges.

The JRP:

- Established a new generation of quantum voltage systems for synthesizing and measuring waveforms - enabling numerous previously unavailable calibration methods based on an intrinsically stable quantum effect (i.e. the Josephson Effect).
- Established methods for the calibration of thermal converters, ADCs and DACs, inductive dividers, amplifiers, spectrum analysers, waveform generators, AC bridges and other instruments with a frequency dependent response.
- Carried out a successful on-site test in an industrial location, esz AG, Eichenau, Germany, which demonstrated the quality and robustness of quantum-based voltage standards. Two technology transfer projects in Germany have also started to make the new $\text{Nb}_x\text{Si}_{1-x}$ fabrication process commercially available and two companies, Supracon and esz AG, have expressed an interest in this commercialisation.

3.2.20 ULQHE: Enabling ultimate metrological Quantum Hall Effect (QHE) devices

The Quantum Hall Effect (QHE) has been the official representation of the electrical resistance unit since 1990. It provides a quantised resistance which is dependent on the electron charge and Planck constant. It is extremely reproducible, with typical uncertainties as low as 10^{-9} and provides the ability to link the ohm (Ω) to fundamental physical constants. This project aimed to deepen the understanding of QHE and develop the next generation of QHE based resistance standards with improved performances that match current industrial needs. This included developing QHE standards, making them easier to use and implement, at reduced costs, and establishing a wide quantised resistance scale ideally from 100 Ω – 1 M Ω . To do this, the project aimed to investigate new devices (Quantum Hall Arrays (QHARS)) and the use of novel materials, such as graphene in QHE devices.

The uncertainty of QHE in Gallium Arsenide (GaAs) (commonly used to fabricate QHE-based resistance standards) was demonstrated using the quantum Wheatstone bridge technique to be as low as 3×10^{-11} , one order of magnitude lower than the previous best quantisation tests. The quantisation of the Hall resistance in the fractional QHE regime was carried out for the first time in high mobility ($10^7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) GaAs (accuracy within 3×10^{-8}). The project pioneered the development of a reliable fabrication process of QHE devices adapted for metrological measurement from graphene exfoliated from graphite, although some limitations were found.

The project validated the use of low value QHARS as the next generation of quantum resistance standards. These devices, based on a combination of up to 145 Hall bars in series and/or parallel arrays, have been demonstrated to present quantised resistance values ranging from 100 Ω to 1.29 M Ω within uncertainties as low as 10^{-9} . The QHARS are compatible with commercial bridges and can be used to calibrate them. During the QHARS fabrication, a process for producing double vertically stacked two dimensional electron gas (2DEG) from GaAs was also successfully developed. Guidelines for the use and design of QHARS are to be targeted for National Metrology Institutes as the end-users of QHARS devices.

The JRP demonstrated the reliability and robustness of QHE and its underpinning theories by reducing the measurement uncertainty. As a consequence, the project reinforced support for its use in the redefinition of the SI units e.g. the Planck constant (with the watt balance experiment) and the electron charge (with the electron charge quantum metrological triangle experiment).

The JRP developed a new fabrication process for QHE devices using exfoliated graphene. However, the results of the project also demonstrated that exfoliated graphene may not be the ideal choice for the application of QHE to metrology, due to low yield, the small size of the devices, moderate quality of the metallic contacts on graphene, and high sensitivity of QHE in graphene to its chemical environment. Nevertheless, the knowledge acquired by the fabrication process is important for the development of a graphene-based quantum resistance standard and can be used by other applications, such as graphene use in chemical detectors.

3.2.21 EMF and SAR: Traceable measurement of field strength and SAR for the Physical Agents Directive

There are minimum requirements for the protection of workers from risks arising from the exposure to electromagnetic fields (EMF) and waves – as laid down by the European Physical Agents (Electromagnetic Fields) Directive 2004/40/EC. These requirements limit the specific absorption rate (SAR) of radio frequency (RF) power between 100 kHz and 10 GHz, and the incident power flux density (PFD) from 10 GHz to 300 GHz. Existing standards do not comprehensively cover SAR and PFD at these ranges, and so this project aimed to provide traceable measurements of SAR and EMF strength at the most widely used frequencies.

Response measurements were obtained for field sensors exposed to pulsed, multi-frequency and digitally modulated signals. In addition, digital signal properties were assessed (error vector magnitude) and reference liquid and phantom material properties were characterised. These measurements are important for radar and airport EMF systems. New broadband sensors, based on spiral and toothed antennas with diode sensors covering 40 GHz to 300 GHz, and thermal sensors, based on a fibre-coupled semiconductor thermometer for field strength measurements in free-space, were developed and validated. SAR measurement setups were developed and characterised for the assessment of communication signals and reference liquid dielectric material properties. Existing measurement setups and theoretical models (e.g. relating surface currents to internal fields during MRI scanning) were optimised and inter-comparisons on SAR calibrations, on specific heat measurements and on theoretical calculations, were performed. A field generator for a sample container containing fluorescent dyes was produced. Calculations of SAR distribution in artefact standards, phantoms and biological material monolayers, as required for micro-dosimetry, were also performed. Finally, a setup for spatially resolved measurements in a thin film on top of the coplanar waveguide was built and subsequently monitored by thermal tomography.

The JRP provided traceable standards for the sensor calibration of multifrequency signals, signals with large bandwidths and pulse-modulated signals, where previously none existed. The JRP also produced artefact standards for SAR and dielectric properties with an extended frequency range up to 10 GHz. These will be used by wireless communication companies to demonstrate compliance of communication devices with the defined exposure limits. The JRP established facilities for calibrating commercial probes, and extending the frequency range from 45 GHz to 300 GHz.

The JRP input into international standards: Institute of Electrical and Electronics Engineers, Inc. (IEEE) 1309 *'Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz'* and national guidelines: VDI (The Association of German Engineers) VDI/VDE/DGQ/DKD 2622 *'Calibration of measuring equipment for electrical quantities'*.

The JRP validated the use of the computer model 'Virtual Family' for modelling EMF and SAR with human subjects – used by communications companies to design devices such as body-worn antennas.

4 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND THE EXPLOITATION OF RESULTS

4.1 Dissemination

Activities to raise the profile of iMERA-Plus and particularly to promote the outcomes from the Joint Research Projects were undertaken at both programme and JRP level via a number of mechanisms.

4.1.1 Joint Research Project (JRP) dissemination

The JRPs addressed a wide range of topics of importance to a diverse range of stakeholders, including regulators, industry, the healthcare sector, the metrology community, academic research, SMEs, the standardisation community etc. Whilst some activities, such as the publication of papers, conference presentations, workshops and JRP websites are common to most JRPs, others such as the production of reference artefacts, the commercialisation of equipment/devices, the production of industry or sector specific guides, exploitation through industrial or sector based 'user committees' or input to standardisation were more specific dissemination and exploitation activities targeted to a particular type of stakeholder.

The Joint Research Projects included

- More than 300 presentations and 90 posters presented at conferences, workshops and events in many countries, including Europe, South Korea, the USA, China, Brazil, Australia, Argentina, Japan, Singapore and Russia;
- The publication of at least 250 peer-reviewed papers in journals ranging from Physical Review Letters to Metrologia, with at least a further 50 submitted for publication;
- Publication of more than 150 articles and papers in non-peer reviewed journals, conference proceedings and the popular press.
- 8 research thesis
- The publication of a patent and 2 patent applications;
- More than 45 workshops and 25 conferences organised by the JRPs or jointly organised with other organisations;
- Commercialisation of artefacts/products;
- Input to existing, revisions, new or potential documentary standards or technical specifications;
- Provision of Good Practice Guides, provision or input into industry or sector specific guides;

Many JRPs held events and workshops towards the end or just after the completion of the projects or formed a significant component of wider events and conferences, including;

- 22 February 2011 (Braunschweig, Germany) – Advances in Coordinate Measurement Techniques for Industrial Applications workshop, NIMTech JRP
- 27-28 October 2010 (Teddington, UK) - Boltzmann Constant Workshop, Boltzmann constant JRP
- 27-29 October 2010 (Brno, Czech Republic) - NANOTRACE Workshop held as an integral part of the NANOSCALE 2010 seminar,
- 1-3 December 2010 (Torino, Italy) - Optical Clocks Workshop, OCS JRP
- 22-23 March 2011 (Noordwijk, the Netherlands) - Power & Energy Workshop, Power and Energy JRP
- 5-6 April 2011 (Delft, the Netherlands) - Breath Analysis Workshop, Breath Analysis JRP
- 18-20 May 2011 – Joint workshop related to Electricity and magnetism theme, JOSY, ULQHE, NanoSpin JRPs
- 19 May 2011 (Berlin, Germany) - 'Traceability of Complex Biomolecules and Biomarkers in Diagnostics - Effecting Measurement Comparability in Clinical Medicine' Workshop associated with the triennial International Federation of Clinical Chemists Worldlab Conference, Clinbiotrace JRP

- 27 May 2011 (Prague, Czech Republic) – Absolute long distance measurement in air workshop, Long distance JRP
- 22-23 June 2011 (Bern, Switzerland) - e-Mass Workshop in association with the Watt Balance Technical Meeting (WBTM 2011), e-Mass JRP
- 27 June - 1 July 2011 (Braunschweig, Germany) – 5th Single Photon Workshop, qu-Candela JRP
- 5-7 September 2011 (Edinburgh, UK) - Particulate Systems Analysis Conference including a joint session between the Nanoparticles - 'Traceable Characterisation of Nanoparticles' JRP and NIST, USA
- 2-4 November 2011 (Leipzig, Germany) - World Conference on Regenerative Medicine, including contributions from the Regenmed - 'Metrology on a cellular scale for Regenerative Medicine' JRP
- 29 November - 1 December 2011 (Braunschweig, Germany) - Joint External Beam Cancer Therapy and Brachytherapy Workshop in conjunction with the International Conference on Advanced Metrology for Cancer Therapy, EBCT and Brachytherapy JRPs
- 2011 (Rome, Italy) - Final workshop on EMF and SAR immediately following the “10th International Conference of the European Bioelectromagnetic Association” EBEA2011, EMF and SAR JRP.

4.1.2 Programme level dissemination

Information about the programme (at programme and iMERA-Plus level) has been included on the EURAMET website (<http://www.euramet.org/index.php?id=emrp>). Summaries of all 21 JRPs were included together with links to JRP specific websites. EMRP related events have been publicised and updated regularly.

iMERA-Plus was presented at the joint 1st Regional Metrology Organisations Symposium – RMO 2008 / 20th International Metrology Symposium held on 12-15 November 2008 in Cavtat-Dubrovnik, Croatia. An overview of iMERA-Plus and the EMRP was presented at the plenary session of the International Metrology Congress (Metrologie) in Lille in June 2007 and in Paris in June 2009. In addition a special session on Metrology and Health, specifically focussing on 5 of the Health JRPs was included in the 2009 Metrologie Congress. iMERA-Plus and the EMRP were also presented further afield at the 2009 NCSLI Conference in Orlando USA in August 2008.

EURAMET hosted a session of talks at the International Metrology Congress (Metrologie) in Paris in October 2011 entitled 'EMRP: Meeting the industrial challenges of tomorrow'. As part of the event posters were produced for each of the 21 iMERA-Plus JRPs and were on display throughout the 4-day event and were the focal point in the main registration area. The congress attracted more than 800 delegates and exhibitors from industry and academia in Europe and beyond.

EURAMET held an evening event entitled 'The European Metrology Research Programme (EMRP) from iMERA-Plus to Article 185 - Achievements and the Future' at Square Meeting Centre, in Brussels on 29 November 2011. The evening event was held to review the achievements of the iMERA-Plus Joint Research Projects and to explore the future of the EMRP, and covered a range of topics including: how joint metrology research should be embedded in EURAMET's overall strategy and mission; a review of the scientific impact of iMERA-Plus; the status of the EMRP; and considerations for future initiatives. The event attracted key stakeholders from the field of metrology and included speakers representing the Commission and EURAMET's Research Council.

iMERA-Plus and EMRP have been presented at several of the Commission organised ERANET workshops, and the presentations have included explanations of how some of the challenges were tackled.

4.2 Impact from the JRPs

Research within the Joint Research Projects underpinned fundamental research, supported the implementation of Directives, and facilitated the development of more effective, efficient and reliable measurement and processes within industry.

Whilst it is not possible within this report to review the impact of the individual JRPs in detail, highlights from a few example JRPs are considered briefly under 4 stakeholder related groupings – industry, standardisation, regulation and quality of life, and the scientific community.

4.2.1 Support to industry and economic growth

Joint Research Projects within the SI, Length and Electricity and Magnetism Targeted Programmes all generated outputs that were of direct benefit to industrial end users, through enabling industry and other stakeholders to operate or monitor processes more efficiently, enabling the development and effective quantification of products and services and the commercialisation of JRP outputs. Below are just a few examples.

- The qu-Candela JRP developed Predictable Quantum Efficient Detectors (PQED) which have been commercialised and are commercially available from Fitecom Ltd, a Finnish service provider of measuring equipment.
- The Power and Energy JRP introduced new calibration services for power quality based on the technology, protocol methodology and guidelines developed in the project.
- The Nanotrace JRP produced a new transfer standard (transportable actuator), which will be used for the validation of accurate displacement sensors such as interferometric, confocal and capacitive sensors, used in industrial measurements and for fundamental research. The JRP also collaborated with 5 optical component manufacturers and micro displacement actuator manufacturers and identified how to improve and support their manufacturing processes.
- The NIMTech JRP developed a large involute gear standard and M3D3 system to assist industries in assessing the performance of large-scale measurement machines, the implementation of task specific uncertainty measurement and the accurate measurements of complex parts. A new method for verifying the performance of laser trackers was developed that not only improves the available diagnostic information it also reduces the verification time from 6-8 hours to 1 hour. This coupled with the fact it can be implemented as an onsite test in most production environments greatly reduces downtime leads to cost savings.
- The NanoSpin JRP developed new reference samples and techniques for nanomagnetism and spintronics which were transferred to industrial and academic end-users in Germany, Spain and Japan.
- The Long Distance JRP developed techniques and prototype instrumentation to significantly reduce the uncertainty of absolute long distance measurement in air. The prototype spectroscopic thermometer has been used in the development of a commercial oxygen analyser by Gasmeter Technologies Inc. The JRP also produced guidelines for the use of the new techniques and prototypes for measuring absolute distances.
- The JOSY JRP developed a new Nb_xSi_{1-x} fabrication process for use in Josephson array fabrication and two companies have expressed an interest in commercialisation of this technique.
- The EMF and SAR JRP validated the use of the computer model 'Virtual Family' for modelling EMF and SAR with human subjects – used by communications companies to design devices such as body-worn antennas. The JRP also established facilities for calibrating commercial probes, and extending the frequency range from 45 GHz to 300 GHz.

4.2.2 Contributions to standardisation

A number of the JRPs from the Health, Length and Electricity and Magnetism Targeted Programmes contributed directly to documentary standards activities within key standards bodies such as ISO, IEC and also to sector specific bodies such as the IAEA or national bodies.

- The Nanoparticles JRP results, including the JRP's Good Practice Guide on the accurate measurement of spherical nanoparticles, have fed into two international standard committees: *ISO TC229 Nanotechnologies* and *ISO TC24 Particle characterisation including sieving*.
- The EMF and SAR JRP results have been input into the committees related to the international standards: Institute of Electrical and Electronics Engineers, Inc. (IEEE) 1309 '*Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz*' and national guidelines: VDI (The Association of German Engineers) VDI/VDE/DGQ/DKD 2622 '*Calibration of measuring equipment for electrical quantities*'.

- The REGENMED JRP provided input into the following standardisation committees; ISO Technical Committee 150 - *Implants for surgery*, ASTM International Committee F04 - *Medical & Surgical Materials & Devices* and BSI Committee RGM/1 - *Regenerative Medicine*.
- The beam quality correction factors (kQ factors) developed in the EBCT JRP are being incorporated into an update of the German standard DIN 6800-2 '*Procedures of dosimetry with probe type detectors for photon and electron radiation - Part 2*'. The kQ factors will also be incorporated in a future version of the IAEA report TRS 398 '*Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water*'. The JRP also input to the redrafting of IEC62555 draft standard on HITU power measurement which has been circulated as a Committee Draft for Vote.
- The results of the Brachytherapy JRP have been input into an AFNOR working group, which is a mirror of ISO TC 85/SC2 WG22 '*Dosimetry and related protocols in medical applications of ionizing radiation*' and have fed into the revision of DIN standard 6809-2 '*Clinical dosimetry; Brachytherapy with sealed gamma sources*'.
- The TRACEBIOACTIVITY JRP submitted new measurement procedures for ion activity to the international Joint Committee for Traceability in Laboratory Medicine (JCTLM).
- The CLINBIOTRACE JRP results may be incorporated or acknowledged in future revisions of ISO TC212 '*Clinical laboratory testing and in vitro diagnostic test systems*' documentary standards.

4.2.3 Support for regulation, Directives and quality of life

Many JRPs provided underpinning methods, techniques to support regulation, Directives and healthcare, enabling additional confidence in conformance assessments.

- The TRACEBIOACTIVITY JRP developed methods that have been used in an on-going European Clinical Trial *Selenium and Prostate Cancer: Clinical Trial on Availability to Prostate Tissue and Effects on Gene Expression* and submitted new measurement procedures for ion activity to the Joint Committee for Traceability in Laboratory Medicine (JCTLM). These new methods have helped to provide traceable and comparable measurements in clinical chemistry, which is a mandatory requirement of the In Vitro Diagnostic Medical Devices 'IVD' - Directive 98/79/EC. Furthermore, the measurement of elements in blood serum was previously restricted to the determination of their total amount, despite the recognition that the clinical effect often depends on the identities and quantities of element species, or ion activities rather than their total amount. By providing new methods for the measurement of ion activity this has improved measurements in medical diagnostics, which is particularly important for calcium, one of the most frequently measured analytes in clinical chemistry, and heteroatom-containing drugs (e.g. sulphur and selenium metabolites), which are used to sensitise cancer cells to chemotherapy
- For the CLINBIOTRACE JRP the World Health Organization (WHO) has expressed an interest in the JRP's multi-parametric protein quantification providing SI traceable values for value assignment of relevant WHO International Standards for biologicals. The JRP has also provided guidance on key parameters identified as influencing immunoassay responses to IVD manufacturers, reference material producers and external quality assurance organisers. The results of the JRP have input in to International Federation of Clinical Chemists guidance, clinical test kits and the organisation of clinical commutability studies. By developing reference measurement systems to provide traceable values for complex biomolecules, such as disease state protein biomarkers, this JRP has enabled comparability between IVD and clinical measurements and improved medical diagnostic efficiency and reliability; thus improving the reliability of patient diagnosis.
- The REGENMED JRP developed measurement technologies and methodologies that enable European companies to meet the requirements for cell characterisation, as defined in the Advanced Therapy Medicinal Product Directive 2009/120/EC. The JRP also helped cell therapy companies to develop cell characterisation techniques that do not rely on animal testing. By improving cell characterisation the JRP helped to define cost effective metrics for assessing the consistency of products containing living cells and to support the use of regenerative medicine. The use of regenerative medicine is important as it could provide healthcare providers and governments with significant savings in healthcare; growing new

cells to replace damaged or diseased tissue removes the need for patient long-term drug treatment and the possibility of adverse side effects.

- The results of the EBCT JRP supported two national dose verification studies for Intensity Modulated Radiation Therapy in Belgium and the UK. By verifying the dose provided by IMRT this should improve the accuracy of the dose of radiotherapy to tumours, while sparing healthy tissue and improving cancer patient treatment and survival rates.
- The Brachytherapy JRP established traceable measurements of brachytherapy radiation sources using absorbed dose to water (D_w) primary standards. These new D_w standards will simplify existing measurements and should reduce the uncertainty in the dose at the clinical level for cancer treatment to below 5 %. Brachytherapy is a cancer radiotherapy approach where small, sealed radioactive sources are placed inside, or in close proximity to, the area requiring treatment. By reducing the dose uncertainty this JRP will help to improve the accuracy of the placement of the radioactive sources which should increase the dose of radiotherapy to tumours and in turn help to improve cancer patient treatment.
- The Power and Energy developed techniques to reduce errors in conformance testing for the regulation of electrical appliances to help protect the multi-billion euro electrical goods industry and to protect the electricity network from exposure to sub-standard equipment. This will support an EU regulatory framework that oversees the market for electrical goods and power generation and help to deliver of an electricity supply of the highest quality - free from momentary voltage interruptions and interference, as required by European industry and commerce.
- The EMF and SAR JRP produced artefact standards for SAR and dielectric properties with an extended frequency range up to 10 GHz. These will be used by wireless communication companies to demonstrate compliance of communication devices with the defined exposure limits, such as in the Physical Agents (Electromagnetic Fields) Directive 2004/40/EC. By helping to demonstrate the compliance of communication devices to the European Physical Agents (Electromagnetic Fields) Directive 2004/40/EC this JRP will support the protection of workers from the risks arising from the exposure to electromagnetic fields (EMF) and waves.

4.2.4 Support for the scientific community

The impact on the scientific community includes the wider scientific community as well as the metrology community. All JRPs contributed to the science knowledge base

- The Boltzmann constant JRP reduced the uncertainty associated with the measurement of the Boltzmann constant k by a factor of 1.5 and submitted results to CODATA for evaluation. It is anticipated that as a result of the JRP, the final uncertainty for k will be reduced to a temperature equivalent of $u(k=1) \approx 0.25$ mK, by the time of the redefinition of the kelvin.
- The OCS JRP developed three Sr clocks with significant improved frequency stability. The clocks will be at the heart of two future space missions: ACES/PHARAO and STE-QUEST.
- The JOSY JRP established a new generation of quantum voltage systems for synthesizing and measuring waveforms – thus enabling numerous previously unavailable calibration methods based on an intrinsically stable quantum effect (i.e. the Josephson Effect).

4.3 The Impact of iMERA-Plus

Even at its launch the European metrology community regarded and hoped that iMERA-Plus would prove an effective stepping stone towards the full scale European Metrology Programme delivered via an Article 185, and this has certainly proved the case. Many of the strategic and practical approaches from iMERA-Plus have been taken forward to A185 with only very minor modifications, whilst in a few cases improvements have been identified and incorporated into the A185.

4.3.1 Benefits of collaboration

The metrology community has always needed to collaborate internationally. Improved measurement ability can only support trade or regulation if all necessary parties can access that measurement locally – agreeing on how to measure, and agreeing on the results of measurement across the world are the prime goals.

When EUROMET was formed it devised processes for providing access to infrastructure, formalising traceability agreements and collaborating in research. The research process however was minimal – a group of technical experts from different members could agree to work together, they would register their intention with EUROMET (the predecessor of EURAMET) and report annually. If an external body imposed a timetable (e.g. developing technical input for a documentary standard) then resources could be aligned and progress made, but many projects made slow progress because the priorities were not agreed at a high enough level between the laboratories. iMERA-Plus changed that radically. For the first time senior managers from the laboratories discussed priorities and agreed the areas where they wanted to drive collaboration. They reserved the resources necessary to ensure selected priorities could be delivered efficiently. They agreed a number of technical objectives that were to be achieved, encouraged consortia to build proposals to deliver those objectives, and allowed a set of independent experts to select the best proposals. The funded projects were required to demonstrate excellent science, good management practice and good engagement with those that would take up the outputs of the project. For the first time realising the benefits of collaboration became a top-down imperative rather than a bottom-up activity. The new model had a number of immediate benefits:

- Coordination at programme level enabled funding bodies, participating organisations and EURAMET to take a strategic coordinated view of the most pressing challenges that needed to be addressed by the metrology community in Europe and for each of the players to take strategic decisions as to which areas were the most important and appropriate for them to contribute to.
- The scale and scope of the JRPs (ranging in size from around 1.6 M€ - 4.6 M€) applied “critical mass” to the prioritised areas. Large teams tackled the priorities and made significant progress much sooner than before.
- The projects delivered a European solution rather than many national ones. When taken to regulators or standards bodies they came as agreed approaches – not as separate competing solutions.
- The programme focussed European metrology resources towards targeted solutions meeting the needs of European stakeholders, increasing the scope of the activities and challenges addressed, reducing fragmentation of activities and resources, and increasing the impact of the research for stakeholders and end users, be it for industrial applications, in support of regulation and healthcare or to underpin the international system of units.

For example, in the Power and Energy JRP the results obtained could only have been achieved through intense collaboration. Every project partner contributed unique expertise. For the first time in the field of power and energy research laboratories and researchers realised a common goal that they could not have reached individually - Two partners were involved in constructing current shunts, two others performed DC tests, again two others characterised the AC properties and one partner carried out computer modelling calculations. Throughout the full duration of the project it was monitored by an active stakeholder committee of more than 20 members. This committee included standardisation bodies (including the IEC), manufacturers of electrical equipment and utilities. Through the stakeholders it will be ensured that power and energy measurement guides and guidelines will be implemented for use within the European Smart Grid.

The iMERA-Plus programme included participants from a diverse range of countries in Europe, from the largest economies to smaller countries that have only joined the European Union in more recent times. The funded JRPs included 5 organisations from 4 countries (Austria, Estonia, Romania and Turkey) that were launching a metrology R&D programme for the first time (Belgium, via SMD, was a participant in the programme but unfortunately although bidding in a number of proposals was not in any of the projects selected for funding) . In addition a further 7 participating organisations were from another 4 countries with relatively small or focussed metrology capabilities or budgets. The programme, which covered multiple areas, enabled these organisations to participate in large collaborative projects in a few selected strategic research areas of national importance, making valued contributions to the projects in their specialist fields. In addition these organisations gained knowledge and expertise from the wider consortium. Examples of this include amongst others the contribution of the Danish NMI (DFM) in the Boltzmann JRP, that of the Estonian NMI (Metrosert) in the qu-Candela JRP, that of the Austrian NMI (BEV/PTP), the Romanian NMI (BRML), the Danish DI (Trescal), the Norwegian NMI (JV), or the Slovenian DI (SIQ) in the Power and Energy JRP, that of the Portuguese DI (ITN) in the Brachytherapy JRP or that of the Estonian NMI (Metrosert) and

Estonian associated laboratory (UT) in the Tracebioactivity JRP. In total approximately half of the JRPs included participation from the newer members.

The programme facilitated coordinated access to major facilities available at collaborators such as beamlines, power distribution networks etc enabling the development, testing and validation of techniques and equipment developed during the JRPs.

4.3.2 Scientific integration - Co-ordination and integration of NMI and national programmes

The integration process started before iMERA-Plus began with the development of the European Metrology Research Programme. As mentioned earlier, the aim was to develop a programme that would address the need to support innovation, quality of life and European policy and the scientific community incorporating the wider horizontal grand challenges in addition to the metrology sector specific needs, and with the ultimate goal of a programme that could be launched under Article 185 of the European Treaty. In developing the programme it was important to understand and incorporate the wider stakeholder needs and to source input from outside the metrology community. As part of the process, consultation was undertaken through a series of stakeholder workshops and focus groups covering health, energy, environment and security. The workshops included representatives from the medical profession, the medical research council, the pharmaceutical industry, the Joint Committee on Traceability in Laboratory Medicine, the power generation industry, the oil and gas industry, an organisation involved in nuclear fusion research, environment agencies, universities and policy Directorate Generals of the European Commission. In addition an extensive roadmapping exercise undertaken by the EUROMET/EURAMET Technical Committees and new focus groups.

iMERA-Plus addressed a subset of four of the areas of most pressing metrological needs identified in the EMRP. These priority areas were sufficiently diverse to make best use of the wide expertise and capabilities within the NMI community, and the Metrology for Health TP addressed projects prioritised by socioeconomic challenges rather than the traditional metrology SI Unit discipline. In setting the indicative budgets for each of the 4 TPs, the EMRP Committee took a joint strategic view on priorities for metrology research across Europe. These decisions were not about individual projects but strategic direction and feed through to national programmes and resource allocations within the NMIs.

The process started before the call was announced, with members within the EURAMET Technical Committees (TC) discussing their future plans, stakeholder needs that they had identified in their countries, and outline work they would like to do to address those needs. Four members of the EMRP Committee were appointed as TP Guardians (one for each TP). Part of their role was to try to ensure that as potential JRPs were identified during the facilitation and proposal process that topics were prioritised where the stakeholder need was clearly demonstrated and the benefits to be gained from the involvement of the metrology community were greatest.

The national programme owners aided integration by relinquishing control over a significant proportion of their national programmes. As proposals were developed they could choose how to spread their resources across the proposals being prepared, but once the bids were submitted they relinquished control, the result was in the hands of the independent referees. Only half the JRP proposals were funded, so they had no guarantee that their priority areas would be successful.

The size of the funded JRPs (around 1.6 M€ - 4.6 M€) reduces fragmentation and duplication. Critical mass was brought to bear on clear objectives, with agreed project plans and enhanced stakeholder engagement. What could have been 15 independent research teams tinkering around a common area became a focused activity driven by the stakeholders.

4.3.3 Financial integration

One of the European Commission's original concepts for ERA-NET Plus projects was that one national body per participating country would be a contracted partner in the ERA-NET Plus project and would act as the hub for distributing funds to other participating organisations within its remit in its country (hub and spoke arrangement). iMERA-Plus was set up using a different approach. The single contracted partner within the EC project was EURAMET e.V. which represents the national metrology institutes (NMIs) and designated institutes (DIs) within the participating countries, and the participating NMIs and DIs were contractually linked third parties to EURAMET. In iMERA-Plus the distribution of Commission funding was therefore undertaken directly by the iMERA-Plus Secretariat on behalf of EURAMET direct to the participating legal entities and not through intermediate national bodies and in

fact the national funding bodies were neither contracted partners nor linked third parties in iMERA-Plus.

iMERA-Plus operated a 'mixed' common pot, with the JRPs funded from a virtual common pot (jointly funded by the participating Member States and the European Commission) whilst the management of phase 2 of the programme ie following the call phase, was entirely funded by the Member States through a real common pot. iMERA-Plus progressed a long way down the route of financial integration. In establishing iMERA-Plus the national funding bodies (usually government ministries) agreed a national funding commitment for the lifetime of the programme, together with a 33 % reserve funding commitment (this reserve was subsequently increased in four countries as a result of their success rate in the call). In many countries the funding bodies indicated the areas they regarded as priority for their country prior to the participating organisations bidding into the projects, but then essentially handed over the decision making process to iMERA-Plus. Once the 21 projects were selected, it was not necessary for participating organisations' to refer back to their national funding bodies for approval and funding to participate in the selected projects. The commitment by the national funding bodies was essentially made at the beginning of the entire process.

This mechanism has proved particularly successful, with no instances of countries being unable to provide their obligated national commitment despite the worldwide economic crisis. Unlike some other ERA-NET Plus projects there have been no occasions where organisations have had to withdraw from selected projects or rely on other countries to top-up the funding. A broadly similar approach has therefore been used for the second phase of the European Metrology Research Programme delivered via the EMRP Article 185.

Twenty countries participated in iMERA-Plus (nineteen countries within the funded JRPs), representing a significant fraction of the European countries, however as this was very much a new way of working a number of countries were naturally cautious about their level of national commitment promised. When the EMRP A185 was initiated it was notable that further countries joined, in addition to all those that had participated in iMERA-Plus. As part of the EMRP A185 EURAMET conducted several surveys covering iMERA-Plus and the A185 which fed into the interim report and formed background information for the Interim Evaluation of the European Metrology Research Programme conducted as an Expert Panel Review commissioned by the European Commission and reporting in late 2011. One finding from the survey was that given the opportunity a number of countries, particularly some of the smaller players, would choose to increase their commitment into the EMRP demonstrating the value they place in the programme and its benefits.

4.3.4 Management integration

iMERA-Plus was the first time that the European metrology community had coordinated large scale collaborative metrology research, across a broad range of stakeholder groupings and technical areas. Overall it proved to be particularly successful. This is in part reflected by the fact that during the course of the programme no organisation withdrew from any of the funded JRPs.

The experience gained from operating iMERA-Plus has enabled the team to demonstrate its competence in handling a programme of significant scale. As a result the EURAMET EMRP Committee unanimously approved the continuation of the fundamentals for the EMRP Article 185, voting for the team managing iMERA-Plus to manage the EMRP Article 185. This fact alone is a key demonstration that the EURAMET members believed that iMERA-Plus was soundly managed; including avoiding potential conflicts of interest and that the integrity of the management process is sound.

The solid and reliable performance under iMERA-Plus was undoubtedly an important element in demonstrating to key decision makers in the Commission, Parliament and Council of Ministers that the metrology Article 185 initiative was credible. Indeed the Ex Ante audit for the Article 185 formally examined iMERA-Plus with a team of auditors spending a number of days at both the Braunschweig and Teddington sites. The auditor's only noted minor points related to iMERA-Plus, all of which were cleared.

4.3.5 How the EMRP Article 185 built on the success of iMERA-Plus

iMERA-Plus provided an ideal opportunity to trial many of the approaches and processes that were to later feature in the EMRP Article 185. The feedback of experience from iMERA-Plus fed into the development of the mechanics of the EMRP under Article 185, it helped shape that initiative, and

indeed the design of all of the A185 processes, with judgements made on sound experience from the existing process.

In the survey conducted by EURAMET the participants indicated overwhelmingly that a two stage call process was a good approach. In the EMRP Article 185, stage 1 of the call has been expanded beyond that used in iMERA-Plus to make the call for topics open to anyone anywhere in the world to submit an idea.

The Review Conference concept proved to be particularly beneficial enabling face-to-face discussions and questioning between the proposers and the referees. Following the Review Conference, feedback was sought from both referees and proposers in the form of a questionnaire and this was used to improve the process, for example providing improved guidance and explanation on the marking criteria, ensuring that referees posed questions to all proposers during the formal question and answer session.

The concept of participating countries providing an additional 'reserve' commitment proved a very successful approach, avoiding the need for a number of countries to have to obtain an additional funding commitment from their national funding body once the JRPs were selected and they discovered that they had been more successful than originally anticipated. In iMERA-Plus four countries did however have to seek and obtain additional funding commitment and hence the decision was made to increase the reserve national commitment from 33 % to 50 % for the EMRP A185.

The A185 EMRP also introduced a number of concepts not trialled in iMERA-Plus including Researcher Grants to engage the wider scientific community in projects.

The iMERA-Plus JRPs have led to a number of follow-on related JRPs funded under the EMRP A185, utilising the outputs from the earlier projects. For example,

- The A185 JRP 'SmartGrid' is refining and deploying the hardware and new algorithms developed for on-site power quality measurement in the iMERA-Plus JRP 'Power & Energy' to make in-situ power quality measurements on various renewable generation equipment and low loss transmission equipment for design validation and compliance with emerging power quality normative standards.
- The A185 JRP 'kNOW' related to the future redefinition of the kilogram is using data obtained in the iMERA-Plus 'NaH' and 'Watt balance' JRPs to develop new measurement capabilities targeted at identifying the cause of the inconsistencies between international data from watt balance and Avogadro experiments.
- The A185 JRP 'DUTy' is using the improved measurement methods developed in the iMERA-Plus 'EBCT' JRP for High-Intensity Focused Ultrasound (HIFU) fields in water to help develop an understanding of the interaction between these fields and tissues.
- The A185 JRP 'MetrExtRT' will use information and measurement techniques and standards developed in the iMERA-Plus JRPs 'Brachytherapy' and 'EBCT' in the development of metrology for radiotherapy using complex radiation fields

4.4 Conclusions

The iMERA-Plus project demonstrated the benefits that can arise from coordinated collaborative research in metrology.

Specifically, it:

- Introduced a step change in collaborative metrology research in Europe and raised it to a level not previously encountered;
- Enabled metrology related research projects to address challenges far beyond that possible for an individual NMI or national metrology system, including those addressing Grand Challenges;
- Enabled the participation in the Joint Research Projects of players, large and small, from 19 countries across Europe;
- Introduced a step change in approach by ministries in the funding of metrology research. For the first time participants committed funds to a common call and jointly funded 21 research projects;
- Reduced fragmentation of metrology research and activities within Europe;

- Demonstrated the capability of EURAMET and its members and associates to manage and deliver a coordinated research programme;
- Identified opportunities to improve the operation of a European collaborative metrology research programme;
- Delivered outcomes from metrology research projects that underpin regulation, healthcare, etc;

iMERA-Plus delivered excellent science and greater scientific, financial and management integration, bringing the metrology community closer through collaboration and competition, thus supporting the European Research Area. It proved to be an excellent pilot for the European Metrology Research Programme, trialling many of the processes and enabling the EMRP Article 185 to be launched and implemented promptly and in an effective manner.

5 PUBLIC WEBSITE ADDRESS AND CONTACT DETAILS

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Links to the websites of the individual Joint Research Projects can be obtained using the iMERA-Plus link above.

Participating organisations:

Coordinating organisation		
European Association Of National Metrology Institutes (EURAMET e.V.)		
Country	Participants in iMERA-Plus	NMI / DI
Austria	Physikalisch-Technischer Pruefdienstdes, Bundesamt Fuer Eich- und Vermessungswesen (BEV/PTP)	NMI
Belgium	Federale Overheidsdienst Economie, KMO, Middenstand en Energie (SMD)	NMI
Czech Republic	Cesky Metrologicky Institut Brno (CMI)	NMI
Denmark	Dansk Fundamental Metrologi (DFM)	NMI
	Trescal A/S (Trescal A/S)	DI
Estonia	AS Metrosert (Metrosert)	NMI
	Tartu Ulikool (UT)	
Finland	Geodeettinen Laitos (FGI)	DI
	Mittatekniikan Keskus (MIKES)	NMI
	Sateilyturvakeskus (STUK)	DI
France	Centre National de la Recherche Scientifique (CNRS)	
	Commissariat a l' Energie Atomique (CEA)	DI
	Conservatoire National des Arts et Metiers (CNAM)	DI
	Laboratoire National de Metrologie et d'Essais (LNE)	NMI
	Observatoire de Paris (OBSPM)	DI

Germany	Physikalisch-Technische Bundesanstalt (PTB)	NMI
Italy	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA)	DI
	Istituto Nazionale di Ricerca Metrologica (INRIM)	NMI
Norway	Justervesenet (JV)	NMI
Portugal	Instituto Português da Qualidade, I.P. (IPQ)	NMI
	Instituto Tecnológico e Nuclear (ITN)	DI
Romania	Biroul Roman de Metrologie Legala (BRML INM)	NMI
Slovakia	Slovenský Metrologický Ústav (SMU)	NMI
Slovenia	Slovenski Institut za Kakovost in Meroslovje (SIQ LJUBLJANA)	DI
	Univerza v Mariboru (UM)	DI
Spain	Centro Español de Metrología (CEM)	NMI
Sweden	SP Sveriges Tekniska Forskningsinstitut Ab* (SP)	NMI
	Strålsäkerhetsmyndigheten (SSM)	DI
Switzerland	Eidgenoessisches Justiz- und Polizeidepartement (METAS)	NMI
The Netherlands	VSL BV (VSL)	NMI
Turkey	TUBITAK Ulusal Metroloji Enstitusu (TUBITAK UME)	NMI
United Kingdom	NPL Management Limited (NPL)	NMI
	LGC Limited (LGC)	NMI
	Commission Of The European Communities - Directorate General Joint Research Centre - JRC (JRC)	