National Measurement System

National Measurement System Programme

for

Electromagnetics and Time Metrology

Programme Document

EMT13

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National Measurement Office

NPL National Physical Laboratory

National Measurement System Programme

for

Electromagnetics and Time

Contract Document EMT13

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The NMS Electromagnetics and Time programme

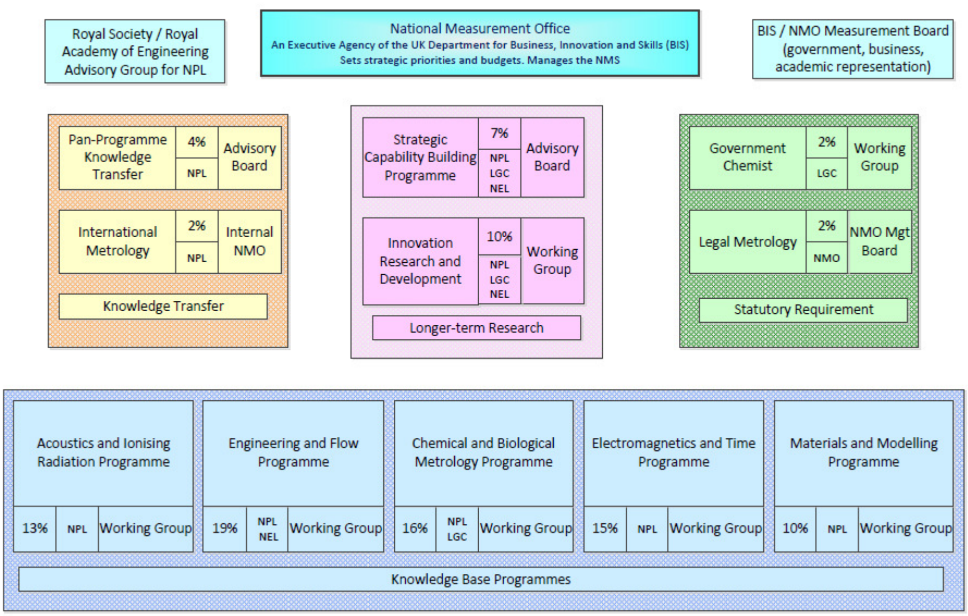
This document provides outlines of the projects in the NMS EMT programme related to the EMT13 contract. The programme is supported by other contracts and detailsof these projects are given in the corresponding programme document.

1. Programme Purpose in the NMS Portfolio

The Electromagnetics and Time Programme is a research programme in the National Measurement System (NMS) portfolio (see figure 1) that delivers:

1. Traceability to the SI units of second, amp, metre, volt and ohm
2. The frequency traceability that underpins the realisation of the metre
3. Time dissemination via the UK National Time Signal and research into fibre and satellite dissemination methods
4. Support for low frequency and DC electrical, RF, Microwave and Terahertz measurement services traceable to the SI
5. New measurement and sensing devices based on counting quanta and quantum phenomena from DC to optical frequencies, in Nano Electrical and Mechanical Systems, Magnetometry and Nano magnetics
6. Traceable measurements related to the performance of high speed electronic systems and communications; circuit boards, connectors and antennas and their effects on health
7. Research into the novel uses of the science and technologies outlined above in new fields

Figure 1. The NMS portfolio



2. Programme characteristics, structure and budgets

This programme is a "knowledge base" with the characteristics shown in figure 2 and is delivered by NPL and its collaborators from academia and industry and in some cases other NMIs.

Figure 2. NMS Knowledge Base Programme Characteristics

NMS Knowledge Base Programme Characteristics

Purpose:

- **Provides core support for the development and maintenance of SI system over the long-term including re-definition of SI units**
- **Maintains and builds on capability already established**
- **Re-definition of SI units may require new science and facilities**
- **Research to address national challenges centred on particular science discipline, not focused on addressing horizontal technology challenges**
- **Provision of traceability to SI through measurement services and development of measurement standards**

The projects in the programme are divided into three themes and to initiate this new programme these themes are supported by theme leaders who are NPL Science Area Leaders. To guide the transition from the 2012 contract, indicative budgets were allocated as outlined in table 1 based on the total science budget for the period April 2012 to March 2013 of £7.9M. Future budgets will be adjusted in line with NMS priorities and in consultation with the working group.

- Time and Frequency Metrology (T+FM); Patrick Gill £2.5m
- Quantum Electrical Metrology (QEM); JT Janssen £2.4m
- Electromagnetics Metrology (EM); David Humphreys and Richard Dudley £2.9m

3. EMRP Opportunities 2012

The programme also benefits from co funding from the European Metrology Research Programme in three 2012 calls:

- SI Broader Scope
- Industry
- Open Excellence

Projects in the EMT theme were very successful in the EMRP assessment process and consequently there are eight projects in the contract which are cofunding new EMRP projects to start in 2013.

4. New Project Structure

Some changes have been made to the project list following the WG meeting. Co-funding for successful EMRP projects have been taken out of previously proposed projects and made into separate projects. In some cases we have introduced 6-month deliverables to take the work from January 2013 to the expected start of the new EMRP projects in July 2013.

As proposed at the Working Group meeting, the work on the NEMS and Nanomagnetism will be focussed on graphene within a new strategic capability project. Also as proposed at the WG meeting, a separate project has been created covering metrology for Smart Antennas. The continuation of work on the room temperature Maser has been moved to the Electromagnetic Metrology Theme wher it could be developed as a microwave amplifier using the skills of NPL's Electromagnetic Team.

No deliverables have been contracted which start later than December 2013. The proposed future developments are kept in the two-page descriptions for reference but shaded out in grey.

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Technical Theme

Quantum Electrical Metrology

Science Area Leader

JT Janssen

Project No.	EMT 13008	Price to NMO	£337.5k
Project Title	**DC & LF Core Capability and Infrastructure**	Co-funding target	
Lead Scientist	N/A	Start Date	01/04/2013
Scientist Team	Jonathan Williams & Measurment Service Team	End Date	31/12/2013

Summary

To provide the facilities, capability and expertise necessary to disseminate DC and low frequency measurements to industry, through the provision of measurement services, consultancies and support for R&D. To ensure these measurement standards are harmonized with those of the UK's trading partners through intercomparisons, ensuring mutual recognition.

The Need

This project supports the fundamental infrastructure, facilities and expertise to deliver the traceable measurement services to industry required by the NMS strategy and directly supports the R&D projects in the Electromagnetic and Time Programme.

To be competitive in a global market, every nation must ensure its industry has access to suitable measurement standards, in which there is universal confidence. In most cases, these standards are provided by UKAS accredited calibration and test houses, however these require traceability to national standards that are coordinated with those of our trading partners. Through participation in international comparisons, systematic errors can be identified, addressed and confidence maintained.

A comparison of Calibration Measurement Capabilities (CMCs) can be made by accessing the BIPM CMC database here: http://kcdb.bipm.org/appendixC/default.asp. Also NPL's performance in intercomparisons can be viewed in the Key Comparison Database here: http://kcdb.bipm.org/default.asp.In particular, NPL is the established world leader in the Power Quality field, utilising novel techniques in digital sampling and waveform analysis. For example NPL has produced and delivered a number of Smart Power Quality Analysers for other NMIs.

The Solution

1) Ensure that the necessary facilities and expertise are available to provide the wide range of relevant measurement services to industry to underpin UK innovation and competitiveness.
2) Participate in intercomparisons to ensure international acceptance of the NMS capabilities.
3) Incorporate new capabilities development, e.g. a significant upgrade is planned for the Cryogenic Current Comparator, enabling more precise and efficient measurements, both in terms of man-power and liquid Helium usage.

Project Description (including summary of technical work)

This project covers the following capability areas: voltage, resistance, AC/DC transfer, current transformers, capacitance, inductance, inductive voltage dividers and AC power, including harmonic analysers and flicker meters.
The facilities include the Josephson junction array primary voltage standard, quantised Hall effect primary resistance standard, cryogenic current comparator ratio bridges, capacitance traceability and measurements bridges, AC inductance bridges, inductive voltage divider calibration systems, as well as AC power and power quality measurement systems.

The technical work would include:

- Calibrate, verify, service and repair all relevant equipment and facilities to maintain capability and infrastructure necessary for the delivery of our measurement services, both externally and internally.
- Demonstrate capability nationally, through UKAS and LRQA audits, and internationally through peer review of CIPM Calibration Measurement Capabilities.
- Safeguard UK interests by scrutinizing CMC claims made by other NMIs to ensure the validity of calibration certificates issued through the Mutual Recognition Arrangement.
- Coordinate UK electrical traceability with that of other countries through participation in, and piloting of, EURAMET and CCEM international comparisons.
- Provide traceability for electrical standards to UKAS and other laboratories through provision of the measurement services underpinned by the project.
- Provide access to facilities and expertise through measurement consultancies.
- Keep staff expertise up-to-date through workshops, conferences and standards.

Impact and Benefits

There are approximately 430 certificates issued to industry per year. Traceability provided to UKAS labs, providing very significant fan-out. Confidence in measurement through traceability to SI units, internationally peer reviewed through the CIPM MRA. To enable industry to develop new innovative products and ensure they meet current standards. A particular example is harmonic analysers and flicker meters, for which very exacting standards exist, which require comprehensive testing of both the hardware and software. The standards maintained through this project also underpin research in other programmes within the NMS.

Support for Programme Challenge, Roadmaps, Government Strategies

The DC and low frequency facilities, expertise and services underpin the following strategic areas as outlined in the NMS strategy: Traceable Metrology and UKAS – "Ensure calibration and testing laboratories are adequately supported by the NMS infrastructure through the provision of traceable measurement standards", "provide world class statutory and commercial measurement services" . It also supports the NMS Energy Challenge by ensuring power quality measurements are traceable using NPLs Smart PQ capability.

Synergies with other projects / programmes

This project will provide some of the basic infrastructure and traceability required for voltage, resistance and ac impedance for many other projects. For example, thermometry requires resistance, load cells require voltage, radioactivity measurements require capacitance and dc magnetic flux requires inductance.

Adoption of new capabilities from research projects is demonstrated by the update of the prototype Cryogenic Current Comparators (proposed in this EMT programme) improving technical capability as well as making the infrastructure more reliable and therefore maintainable.

Risks

On the whole the risks relating to this project are low, given the facilities and expertise are in existence. In addition, an essential element of the project is concerned with solving unanticipated problems with the facilities as they arise, therefore there is an in-built risk mitigation mechanism. Remaining risks are:

1) Loss of expert staff in the voltage, resistance and ac impedance areas could affect our ability to maintain our existing capability.
2) Significant problems with the building that are outside our immediate control, in particular the temperature control, floods etc.

The nature of this project is such that it tends to mitigate risks on other projects by ensuring the underlying infrastructure and expertise is operational and available.

Knowledge Transfer and Exploitation

The key method for knowledge transfer is through the provision of measurement services to industry and the advice provided to end users to ensure the measurements offered meet their needs. In addition:

- Presentations/papers at workshops and conferences
- Updates to the Measurement Services pages on the NPL website, providing technical information
- Articles for NPL Newsletters
- Dissemination of information to user groups
- Reviewing papers for journals
- Participation in training courses
- Visits to industrial customers to understand their present and future technical needs

Co-funding and Collaborators

Approximately £342k revenue per year from industry from measurement services alone and given that the capability maintained enables NPL to operate as an NMI, it supports the research capability necessary for the EMRP and TSB projects.

Deliverables

1	**Start: 01/04/13**	**End: 31/12/2013**	**:ost:**

Deliverable title: DC & LF Facilities and Expertise maintained

Evidence: Provide traceability for DC & LF quantities to industry through the provision of measurement services. Demonstrate on-going expertise through UKAS/LRQA assessments and participation in intercomparisons.

Project No.	EMT 13009	Price to NMO	£250k
Project Title	**Improved Cryogenic Current Comparators**	Co-funding target	
Lead Scientist	Jonathan Williams	Start Date	01/01/2013
Scientist Team	Jonathan Williams, Dale Henderson, JT Janssen, Stephen Giblin, Jane Ireland	End Date	31/12/2014

Summary

This project will prepare the UK NMS for the forthcoming redefinition of the ampere and invest in cryogen-free operation of the quantum standards. Electrical metrology has benefited from quantum electrical standards operating on a unified basis for more than 20 years. The redefinition of the SI ampere in terms of the elementary charge will place quantum electrical effects at the centre of the SI. Realisations of voltage, resistance and current will all be equivalent and the most practical standard or combination of standards will be deployed according to the particular quantity and decade value being measured. To benefit from this flexibility in the dissemination of the electrical units, an investment in measurement infrastructure, comprising the quantum standards themselves and cryogenic current comparators for ratio measurement is required.

The Need

Quantum electrical effects are at the heart of electrical metrology. Since 1990, the SI units of voltage and resistance have been disseminated in terms of the Josephson and quantised Hall effects respectively using internationally agreed values for the ratios 2e/h and h/e^2. Recent advances in devices for single electron transport have now brought a practical quantum standard of current based on the elementary charge, e, within reach. After the planned redefinition of the SI in terms of the fundamental constants h and e, quantum electrical metrology will take centre stage. The mise en pratique for the ampere will mean that realisations of voltage, current and resistance with any two of the three quantum effects will be equivalent. Thus the most convenient approach can be used for the particular quantity and numerical value being measured. For the first time, it will become more convenient to realise a small electrical current directly in terms of the new ampere rather than via the Josephson and quantised Hall effects. To obtain the greatest benefit from the new SI, a coherent system of measurement systems for the quantum electrical effects and for dissemination to industry is required. In particular, an investment in cryogen-free technology has become a necessity due to the rapidly increasing cost and severe shortage of liquid helium world-wide. A problem which is set to increase further in future.

The Solution

The present capability consisting of the Josephson voltage standard, quantised Hall resistance standard with associated cryogenic current comparator bridges and the quantum current standard, presently still in research and development, will be integrated into a coherent set of apparatus. At the same time, a move to cryogen-free operation will be made to reduce the ongoing consumption of liquid helium as this is becoming a scarce resource. Measurement electronics, cryogenic apparatus and measurement software will be integrated and rationalised. The result will be a turn-key, 'quantum calibrator' for voltage, resistance and current in the new SI.

Project Description (including summary of technical work)

Key technical challenges:

- Integration of two cryogenic current comparators and a Josephson junction array system into a single cryogen-free apparatus at 4 K.
- Integration of a graphene quantised Hall effect sample into a cryogen-free apparatus at <5 T and > 2 K.
- Rationalisation of measurement electronics and software for resistance measurement so as to cover the range 1 Ω to 1 GΩ in a single system involving two cryogenic current comparators
- Routine use of graphene quantised Hall effect samples as a quantum standard of resistance with metrological accuracy

Impact and Benefits

The three quantum effects, at present largely maintained as separate systems supporting individual quantities would become an inter-operable set. For example, for high resistance measurements at the 1 GΩ level, traceability could be via a quantum current standard and the Josephson effect rather than via the quantised Hall effect and a cryogenic current comparator bridge if this is more convenient. The availability of both routes would also confirm the integrity of the quantum-based traceability. The new system would be more adaptable and could be readily configured to meet evolving needs of industrial measurement, particularly in the area of high resistance and small currents. The range of technical apparatus required to provide routine traceability would become greatly reduced with a corresponding reduction in the year on year cost to the NMS. The superior properties of graphene quantised Hall effect devices will lead to a more flexible and easier to operate quantum resistance standard.

NPL's world leading capability, as evidenced by the publications below, will be packaged for the future benefit of precision electrical measurement and support for regular measurement services.

- 'Towards a quantum representation of the ampere using single electron pumps', S.P. Giblin, M. Kataoka, J.D. Fletcher, P. See, T.J.B.M. Janssen, J.P. Griffiths, G.A.C. Jones, I. Farrer & D.A. Ritchie, Nature Communications Volume:3,Article number:930 DOI:doi:10.1038/ncomms1935(2012)

- 'Precision comparison of the quantum Hall effect in graphene and gallium arsenide', T J B M Janssen, J M Williams, N E Fletcher, R Goebel, A Tzalenchuk, R Yakimova, S Lara-Avila, S Kubatkin and V I Fal'ko, Metrologia 49 294 doi:10.1088/0026-1394/49/3/294 (2012)

- 'Cryogenic current comparators and their application to electrical metrology', J. M. Williams IET Science Measurement & Technology, 5, 211-224 (2011)

- 'An automated cryogenic current comparator resistance ratio bridge for routine resistance measurements' J. M. Williams, T. J. B. M. Janssen, G. Rietveld and E. Houtzager Metrologia, 47, 167-174 (2010)

Support for Programme Challenge, Roadmaps, Government Strategies

The project targets the NMS objective of supporting " Next-generation metrology and its application (including the SI units and theirextension)" . The project relates to the Programme roadmap 'Innovative calibration means in electricity/magnetism' and addresses the targets 'Traceability for *V*, *I*, *R* at point of use' and 'Traceability to quantum standards with minimum added uncertainty'. It is a realisation of the new SI based on *h* and *e* and will develop turn-key systems with cryogen-free operation. It will make use of graphene QHR devices, quantized current sources and cryogenic current comparators.
It represents an investment in NMS infrastructure in quantum electrical metrology for the next 10-15 years. It will underpin both leading edge electrical metrology and measurement services.

Synergies with other projects / programmes

The project represents the implementation and exploitation of parallel NMS research into quantum current standards and graphene metrology. Beyond the project, the infrastructure developed will be maintained as part of the support for measurement services.

Risks

- Cryogen-free technology does not deliver the required performance in terms of vibration and temperature stability. This is mitigated by current NMS research in this area and the possibility of using either technology from different suppliers or the of semi-wet or recirculating systems.

Knowledge Transfer and Exploitation

The main dissemination route will be through the use of the system for leading edge metrology and regular measurement services. Technical achievements will be presented at conferences and published in peer-reviewed publications. Improvements in traceability will be represented via NPL's Calibration and Measurement Capabilities (CMC)s and discussion at international groups such as the Consultative Committee for Electricity and Magnetism (CCEM) and the EURAMET TCEM. Specialised training will be provided to visiting metrologists from other national institutes on demand.

Co-funding and Collaborators

EMRP project SIB07 'Qu-Ampere', Realisation of the new SI ampere will deliver devices to this project
AIST, Japan for supply of Josephson arrays suitable for cryogen-free operation

Deliverables

1	**Start: 01/01/2013**	**End: 31/12/2014**	**Cost:**
Deliverable title: To systematically upgrade NPL's cryogenic current comparators. Evidence: Upgrade of "high turns ratio" Cryogenic Current Comparator to a standard, by which the metrological triangle can be realisedwith an uncertainty of 1 in 10^7			
2	**Start: 01/01/14**	**End: 31/12/15**	**Cost:**
Deliverable title: Option - Cryogen free cryogenic current comparators **Evidence**: Two comparators operating with accuracy and stability suitable for measurement services			
3	**Start: 01/01/16**	**End: 31/12/16**	**Cost:**
Deliverable title: Option - Cryogen-free Josephson junction array **Evidence**: Cryogen-free array working with accuracy and stability suitable for measurement services			

Project No.	EMT 13010	Price to NMO	£225k
Project Title	**Superconducting Nano Quantum Devices for Integrated Electrical Intrinsic Standards**	Co-funding target	
Lead Scientist	Jonathan Williams	Start Date	01/10/2013
Scientist Team	Jonathan Williams, Dale Henderson	End Date	30/06/2014

Summary

Digital electrical measurement is now the method of choice for instrument designers. Analog voltages are digitized at the earliest opportunity in the signal path and signal processing is used to filter and analyse the waveform rather than using more costly circuits based on discrete components. The performance of the analog to digital converter (ADC) is therefore central to the ultimate specification of the instrument. Manufacturers of integrated circuits are responding to this trend and have recently brought products to market that represent a step change in performance. These devices are operating at the limit of currently available test instrumentation with the specification dominated in many cases by the performance of the waveform generators and measurement instruments available. This project is aimed at delivering digital electrical metrology directly in terms of the SI using quantum devices. It will deliver the next generation of superconducting devices required for integrated intrinsic standards and will produce a prototype measurement system with co-funding from the EMRP project 'Q-wave'. The ultimate aim is to harness the performance of quantum devices to provide a characterisation capability for analog to digital and digital to analog converters (DACs) at least an order of magnitude beyond the current state of the art in test instrumentation.

The Need

The latest ADC and DAC products have a performance beyond the traceability available to the SI, strongly limiting their range of application in the marketplace. In Europe, Analog Devices who hold half the data converter market, say that 'customers have tough signal chain issues to be solved and we need to design and deliver solutions'. Such solutions can only be delivered with the support of a robust measurement framework for digital electrical measurement, backed up with quantum traceability to the SI.

The Solution

NPL has world leading capability for sampled electrical measurements on the millisecond timescale, using a combination of conventional and quantum electronics. However, measurements on microsecond timescales requires a purely quantum-based measurement instrument capable of recording waveforms (digitizing) up to MHz frequencies directly in terms of *h* and *e*.

Project Description (including summary of technical work)

The technical outcome of the project will be (i)the of measurement of voltage waveforms on the microsecond timescale with part per million accuracy, (ii) reduced complexity at the user interface (potentially leading to wider scale adoption by the NMI community) and, (iii)new understanding of nano-scale superconducting devices and their role in electrical metrology. Delta Sigma topology affords the opportunity to create a digitizer purely from quantum mechanical effects, principally the lossless processing of quanta of magnetic flux (*h*/*e*). Such a quantum digitizer with intrinsic accuracy will be developed at NPL. It is planned to proceed in stages, each offering greater performance and building on the last.

- Build a digitizer using optoelectronic control in the feedback loop; essentially the photonic biasing of Josephson junctions (JJ). The digital filtering and feedback control will be conventional, lossless, but will limit the bandwidth to about 1 MHz This activity will co-fund the EMRP project Q-wave and is NPL's activity in this project, which seeks to bring quantum-based sampled electrical measurements to calibration-tier institutes. NPL will collaborate principally with the PTB (experts on JJ array fabrication) and NPL will design and construct the DS digitizer.
- Improved micron-scale devices will be developed in collaboration with Royal Holloway University of London (RHUL). These will include Josephson junctions and chains for flux to voltage conversion. The devices will be integrated into the digitizer to improve the performance of the input circuit.
- Superconducting devices produced using nano-fabrication techniques will be developed principally in collaboration with the London Centre for Nanotechnology (LCN). NPL will share the design and testing; fabrication will be at the LCN. The work will include measuring the accuracy of comparators (quantifying the gray zone) for voltage level discrimination up to GHz frequencies. Nano-scale devices offer a longer term solution to many of the performance limitations of micron-scale flux quanta-based measurement devices.

Current state of the art in this area is shown by the work of the leading organisations in the field:

NPL – demonstration of opto-electronic biasing of JJs: "The simulation and measurement of the response of Josephson junctions to opto-electronically generated short pulses", Supercond. Sci. Technol. **17** (2004) 815-818

AIST – building on original NPL work: "Generation of constant voltage steps by a Josephson array driven by opto-electronically generated pulses", Physica C 463-465 (2007) 1123-1126

Northrop Grumman – demonstrator delta-sigma converter employing a quantum feedback DAC (though not quantum accurate): "A quantum-accurate two-loop data converter", IEEE Transactions on Applied Superconductivity **19** (2009) 676-679

Impact and Benefits The project portfolio of digital electrical metrology underpins the step change in the application of sampled electrical measurements in the marketplace. European sales of data converters are growing at 9% a year and represent a significant part of Analog Devices $3billion revenues*. IEEE Standard 1241-2010, "Terminology and Test Methods for Analog-to-Digital Converters", calls for test equipment with a specification which significantly exceeds the desired performance of the ADC under evaluation, for example 'the input sine-wave source shall produce sinusoids of high spectral purity, harmonic distortion lower than that of the ADC under test'. The British Standard BS IEC 60748-4-3:2006, "Interface integrated circuits – dynamic criteria for analogue-digital converters (ADC)", comments on the challenge of the dynamic characterisation of an ADC: 'Linearity errors of an ADC are dependent on the amplitude of the input signal and its rate of change. Not so well known is that linearity errors also depend on the instantaneous amplitude distribution, ie the amplitude probability density function (APDF) of the input signal. This source of error is usually a result of localized heating effects in the integrated circuit and is dependent on ADC architecture and internal circuit layout.' The specification of currently available test equipment is now starting to limit the testing of the latest generation of ADCs and DACs. This means that there is a barrier to applying these devices to real-world measurements because they cannot be characterised by existing metrological techniques. This project portfolio will break through this barrier by providing traceability for sampled electrical measurements through the direct use of quantum standards in the measurement process.

As an early example of impact, in the last year NPL has enabled the development of a new product by a UK SME using its existing quantum traceability for sampled electrical measurements on the millisecond timescale. The product uses a state of the art ADC and signal chain. * 'Working at a higher level', Dr Carsten Suckrow, Analog Devices, interviewed by New Electronics magazine.

Support for Programme Challenge, Roadmaps, Government Strategies

'Next Generation Digital Electrical Metrology' is an example of 'Application of new knowledge to innovation in goods and services' in the NMS Strategy 2011-15. The project area is represented on the theme roadmap "Innovation in electrical / magnetic calibration" by the target "Traceability for sampled electrical measurements", the experimental realisation "Innovation in electrical / magnetic calibration", the metrological application "Josephson based DACs and ADCs", making use of the enabling science and technology "Improved fabrication and circuit integration (array technology, microwave-IC, cryo-packaging), Application of RSFQ to Josephson voltage.The portfolio represented by this project and. The research will 'enable innovation by providing new and improved measurement references and techniques' in the area of digital electrical metrology.

Synergies with other projects / programmes This project will provide the new technology to take the traceability for sampled electrical measurements from the millisecond to the microsecond timescale. It builds on the NMS 'Next Generation Digital Electrical Metrology' project.

Risks

- The nano-fabricated devices are at the leading edge of the science so there is risk that they won't deliver the required performance in the expected timescale. The mitigation is to stage via photonic hybrid, then micro-scale.
- Aims and objectives of collaborators diverge from the project aims. The project has several collaborators.

Knowledge Transfer and Exploitation Knowledge of device design and fabrication will be exploited through partners PTB and AIST who are experts in large scale fabrication. Resulting practical devices will be exploited in the NMS Next Generation Digital Electrical Metrology Project and the EMRP "Q-Wave: Metrology for sampled electrical measurements – dissemination of quantum based voltages and waveform" (when funded). Scientific advances will be shared with the research community via presentations and peer-reviewed publications. The resulting improvements in data conversion capability will underpin new products in multiple sectors, for example, aerospace, health, automotive and communications.

Co-funding and Collaborators

- EMRP project "Q-Wave: Metrology for sampled electrical measurements – dissemination of quantum based voltages and waveform" in preparation under SI Broader Scope II, 2012
- London Centre for Nanotechnology (LCN) for design and fabrication of nano-scale Josephson junctions and nano-wires
- Royal Holloway University of London (RHUL) for design and fabrication of Josephson junctions and chains
- PTB, JJ technology and (Rapid Switching of Single Flux Quanta) RSFQ circuits (irrespective of EMRP funding)

Deliverables

1	**Start: 01/10/13**	**End: 30/06/14**	**Cost:**
Deliverable title: Improved micron-scale devices for delta-sigma input stage **Evidence**: Devices to include Josephson Junctions and chains for flux to voltage conversion			
2	**Start: 01/07/14**	**End: 31/12/15**	**Cost:**
Deliverable title: Quantify the 'gray zone' of a Josephson comparator **Evidence**: Comparator accuracy evaluated at NPL for voltage level discrimination up to GHz frequencies			

Project No.	EMT 13011	Price to NMO	£249k
Project Title	**Co funding for EMRP Project Q wave SIB59**	Co-funding target	180k in place
Lead Scientist	Jonathan Williams	Start Date	01/07/13
Scientist Team	Dale Henderson, Jane Ireland,	Stage End Date	30/06/16

Summary

This project represents the NPL contribution to the Q-Wave JRP, forming part of the EMRP's SI Broader Scope portfolio. The central problem that is being addressed in this JRP is the lack of instrumentation and knowledge that is necessary to provide direct and efficient traceability to the SI volt for analogue-to-digital and digital-to-analogue converters operating in the DC to 10 MHz range.

The Need

The demand for time-resolved, precision voltage measurements, including traceability to the SI volt, is caused by the recent breakthrough in resolution and stability of analogue-to-digital converters (ADC) and digital-to-analogue converters (DAC) to beyond 16-18 bits. Current traceability is by thermal transfer standard, and this route is no longer adequately applicable to the underpinning of the instrumentation used for ADC/DAC characterisation. This assessment is shared by "Letters of Support", which state: *"We are concerned that the current traceability route of thermal transfer will be insufficient in the medium term ..."* (J.C. Gust, Fluke); *"We are concerned that the present traceability in this field will be insufficient in the near future ..."* (A. Di Nozzi, Teledyne LeCroy); *When thinking of recent releases from semiconductor and instrumentation manufacturers with their latest resolutions and speed the demand of calibration will rapidly be limited by classical methods."* (P.M. Fleischmann, ESZ AG) The work supports innovation in Digital Electrical Metrology and falls within the remit for public support because of the size of this challenge in fundamental SI metrology.

The Solution

The aim of the JRP is to provide direct and efficient traceability to the SI volt for analogue-to-digital (ADC) and digital-to-analogue converters (DAC) operating in the frequency range from DC to 10 MHz. These procedures comprise the investigation and measurement of arbitrary waveform signals. Therefore, the JRP addresses the scientific and technical objectives to:

- Realise a measurement system based on the Josephson effect for the dynamic calibration of analogue-to-digital converters.
- Establish dissemination methods based on state of the art instrumentation and converters, as used in national metrology institutes and the next tier of users in the calibration and test sectors, including techniques for both repetitive and single shot waveforms.
- Improve digital signal processing techniques and evaluate their contribution to the measurement uncertainty.

Project Description (including summary of technical work)

The NPL contribution to the JRP is concentrated in work package 2: Josephson synthesizer and A to D converter. The aim of this work package is to produce a quantum-based analogue-to-digital converter for direct measurement of arbitrary waveforms in terms of the Josephson effect. Up to 10 Josephson junction arrays connected in series as a synthesiser will form a quantum voltage reference. The converter will use delta-sigma modulation techniques in the feedback loop to achieve the desired combination of sampling rate and resolution. The perfect quantisation of electrical pulses provided by the Josephson array means that the digital code generated by the converter can be directly related to the quantity 2e/h used to maintain the volt in the SI system. The type B uncertainty of the converter will therefore be limited only by the performance of the input stage (delta) and the gain of the integrators in the feedback loop (sigma). The Josephson junction arrays will be developed by PTB in work package 1**.** The direct traceability to the maintained SI volt provided by the converter will be exploited in work package 3 where quantum referenced waveforms will be used as a reference for practical sampled voltage measurements.

Impact and Benefits

The results of this JRP will impact directly in the electrical quantum standards community mainly formed by National Metrology Institutes (NMI) and high-level calibration laboratories. It will also have impact in the electrical low-frequency community as well as in communities involved in electrical sampling measurements and in dynamic quantities. These communities comprise NMIs, laboratories, and industry. This JRP will establish a new infrastructure in the European NMI community for traceability for voltage waveforms directly to the SI representation of the volt in terms of the Josephson effect. The latest generation of DACs, when integrated into systems to be developed in this JRP, will be able to provide top level traceability to end users directly in terms of the quantum standard, without having to use thermal transfer standards as an intermediate step. The outputs of this JRP are directly relevant to the

following standards: • IEEE Std. 1241-2010 “Terminology and Test Methods for Analog-to-Digital Converters” • IEEE Std. 181-2011 “Transitions, Pulses, and Related Waveforms” • IEEE Std. 1057-2007 “Digitizing Waveform Recorders” • IEEE Std. 1658-2011 “Terminology and Test Methods for Digital-to-Analog Converter Devices” • IEC 60748-4-3:2006 “Semiconductor Devices – Integrated Circuits – Part 4-3: Interface integrated Circuits – Dynamic Criteria for Analogue-Digital Converters (ADC).
Support for Programme Challenge, Roadmaps, Government Strategies The JRP is set in the context of The EMRP Outline 2008, section I.1.2.2, “Focussed single discipline and applied metrology” which refers to advanced realisations of derived SI units and applied metrology to support innovation, products and services. Within the SI it is directed at the provision of “intrinsically referenced standards” by exploiting the quantum standard of voltage, in the form of the Josephson effect, to provide direct traceability for dynamically varying or AC voltages. In this way it is aimed specifically at broadening the scope of the SI to provide quantum traceability for non-stationary voltages for the first time, especially for arbitrary waveforms for which there is no direct route at all at present. This JRP integrates the national metrology research programmes of the 12 countries that make up the JRP-Consortium. The different expertise of each partner is jointly used to fulfil the objectives of the JRP that are impossible to be covered by a single NMI due to the range of skills and resources required. The JRP will enable them to align their national activities to deliver a much more challenging result and, at the same time, establish a common technique to be exploited by the partners after the conclusion of the project.
Synergies with other projects / programmes The work is complemented by the project *Superconducting Nano Quantum Devices for Integrated Electrical Intrinsic Standards*, within the EMT Programme, which seeks to develop novel devices to be applied in this area of SI traceability.
Risks • Multiple-parallel connection of pulse-driven Josephson junction arrays does not reach desired multiplier of 10 required for 1 V output. This is highly likely as approach is completely new and, as such, is a key research element of the project. A resistive divider method will be used instead to reach an output of 1 V. • Opto-electronic devices for cryogenic operation do not achieve required performance. This is highly likely as this work has limited prior art and the specification is challenging. Room temperature photodiodes have previously been demonstrated to work in this application. The required series connection of array s can be achieved with room temperature devices but more coaxial cables into the cryostat will be required.
Knowledge Transfer and Exploitation The outcomes of research in the JRP will be presented as scientific publications in peer reviewed journals, e.g. IEEE Transaction on Instrumentation and Measurement, Metrologia, Measurement Science and Technology, Superconductor Science and Technology, and IEEE Transaction on Applied Superconductivity. Technical results will be presented at leading international conferences such as Conference on Precision Electromagnetic Measurements (CPEM), NCSL International, Metrologie, Applied Superconductivity Conference (ASC), and European Conference on Applied Super¬conductivity (EUCAS). The JRP will influence the Waveform Generation Measurement and Analysis Technical Committee of the IEEE Standards Association by seeking an invited presentation on the project outputs, both theoretical and experimental (task 4.2.2). The consortium will demonstrate how the current limitation in test methods and traceability available can be overcome by direct traceability to the SI for sampled electrical measurements. CEM, MIKES, and SIQ supported by other partners will contact and inform the relevant technical committees of IEEE and IEC.
Co-funding and Collaborators The JRP consortium consists of 12 laboratories: PTB, CEM, CMI, EJPD, INRIM, JV MIKES, NPL, SIQ, SP, TUBITAK and VSL.
Deliverables

1	**Start: 1/7/13**	**End: 30/6/16**	**Cost:**
Deliverable title: Co funding for EMRP project Q Wave			

Project No.	EMT 13012	Price to NMO	£625k
Project Title	**Quantum Current Standard**	Co-funding target	
Project Lead	Masaya Kataoka	Start Date	01/04/2013
Project Team	JT Janssen, Stephen Giblin, Patrick See, Jonathan Fletcher	End Date	31/12/2014

Summary

The main objective is to develop single-electron semiconductor device technology to provide technical underpinning for (1) redefinition of the SI base unit ampere, and (2) future quantum technology applications. We will develop semiconductor devices that will trap, manipulate and emit single electrons with high accuracy and precision so that they can be used to provide an accurate reference current that links the ampere and Hz (frequency) through a fundamental constant *e*, the elementary charge, and also can be used as a reliable source of single-electrons for quantum device applications such as quantum information processing and communications.

The Need

The re-definitions of the kilogram and ampere must be based on (1) empirical evidence that the fundamental constants *h* and *e* have the same values in different types of quantum device, and (2) on the availability of devices, which can realise the new definition. The key requirement for both these points, in the case of the ampere, is an accurate, high-speed electron pump delivering a current in the nA-range. This requirement for an accurate single-electron source is also true for the practical realisations of future single-electron quantum device technologies where precise and accurate control of single electrons are needed. NPL is the leading National Measurement Institute investigating the metrological properties of high-current electron pumps [recent publications: Nature Physics 3, 343 (2007), PRL 106, 126801 (2011), Nature Communications 3:930 (2012)]. Especially, our recent measurement with 1 part in 10^6 accuracy represents the worlds' state-of-the art for single-electron pumps.

The Solution

Towards the realisation of a quantum current standard, we will focus our effort on the most promising technology; semiconductor quantum-dot tunable barrier pump. In this system, a quantisation accuracy of 1 part in 10^6 with 150 pA current level has been demonstrated so far. There is a clear technology path for enhancing the current level to 1 nA with an accuracy of 1 part in 10^7, required for practical quantum current standards. We will develop measurement technologies to resolve the current quantisation with an uncertainty of 1 part in 10^7, as well as investigating the underlining physics of the electron pump dynamics in order to enhance the current quantisation accuracy even further.

Project Description (including summary of technical work)

Direct-gated electron pumps (fabricated using standard methods) will be investigated in ultra-high accuracy measurement systems based on cryogenic current comparators. Initially measurements will be aimed at proving the accuracy of the pumps. Later, if the pumps are sufficiently accurate, the same measurement system will be used to run the "metrological triangle" experiment comparing measurements of the ampere, volt and ohm.

01: Measurement of the pump accuracy will be performed by comparing the pump current with a reference current traceable to quantum standards of voltage and resistance. As we drive the pump outside its usual working range (for example, by increasing the frequency), a change in current, corresponding to pumping errors will be measured. The parameter space for error-free operation will be established.

02: We have recently found that, by using an optimised waveform shape, the pump operation frequency can be increased up to ~ 1 GHz, producing a current as large as 150 pA, without losing the quantisation accuracy of 1 part in 10^6. We aim to double the current by using two pumps in parallel, in order to achieve the measurement uncertainty of 1 part in 10^7.

03: Point-contact charge detectors will be fabricated via the same process as the electron pumps in **01** and **02**. Initial experiments on stand-alone detectors will establish their noise and charge resolution. Integrated pump / detectors will be used to investigate the dynamics of the electron pump error mechanism.

04: In order to most efficiently exploit shaped waveform drive for current quantisation improvement, the electron pump mechanisms need to be understood at the microscopic level. We will use shaped waveforms to investigate the pump mechanisms in time domain.

05: In order to achieve current quantisation accuracy with uncertainty of 1 part in 10^7, one critical criterion is the plateau flatness. The current value must be robust to fluctuations in control parameters (such as gate voltage, rf excitation amplitude etc). We will establish the highest achievable current plateau flatness with resolution of 1 part in 10^7.

06: The vulnerability of the electrons in a certain part of the cycle to external excitation will be exploited to develop single microwave photon detectors. A loss in the current quantisation, current noise, charge detector will be used to detect microwave absorption events. The information obtained here in turn will be exploited to suppress electron pump errors due to external radiation sources.

Impact and Benefits

This primary electrical metrology capability will underpin the electrical measurement infrastructure in the future increasing the robustness of a globally uniform system of units for the first time based on the fundamental constants of nature. Re-defining the ampere in terms of the electron charge will provide society and industry with a system of electrical units able to handle the considerable technical challenges that the 21 'st century is likely to present and enabling the development of new technologies based on quantum devices.

Support for Programme Challenge, Roadmaps, Government Strategies

The results of the project will directly support the top-level aims of the NMS Strategy to 1) "maintain NPL's leading international status" "shaping (and leading) European priorities for metrology research".2) "Make a significant contribution to the evidence base for the redefinition of selected SI units by CGPM and take a leading role in the development of a world measurement system by actively researching new methods when they become available.3) specifically in this case provide the underpinning scientific foundation for the SI base unit of the Ampere "defined in terms of the fundamental constants of nature". This project is also perfectly aligned with NPLs' vision for "The new Quantum SI" as set out in the 2020 Metrology strategy document.

Synergies with other projects / programmes

The methodologies of low-temperature refrigeration, and precise electrical measurement are shared with at least five other projects in the NMS programme. There is also synergy with the instrument development and maintenance of the SI electrical units undertaken within the physical program - indeed the access to primary standards is what makes NPL uniquely placed to develop the metrological potential of electron pumps.

Risks

This project has a fundamental risk is that the project will uncover reasons why the proposed types of electron pump are not sufficiently accurate for a re-definition of the ampere. In this case the project will have a scientific output (explanation of the error mechanisms) but not achieve its metrological goal. However, based on our previous research and theoretical modeling of the pumping mechanism we anticipate this to be a low-level risk.

Knowledge Transfer and Exploitation

The top-level aim is to provide a metrological triangle result for input into the ampere redefinition. The project will also yield scientific papers and presentations aimed at both technical and general audiences. The project results would be targeted at journals on the level of Nature / Science. Potential spin-off areas include quantum electron optic experiments, on-demand single-photon source (both covered in the SR Project: Single Quantum Device Technologies), single microwave/THz photon detector (EMRP MICROPHOTON),

Co-funding and Collaborators

"Quantum Ampere" from May 2012 until April 2015.
EMRP 2012 Open Excellence "MICROPHOTON" from July 2013 until June 2016
Our external collaborations include:
PTB through EMRP project Quantum Ampere, running until 2015. University of Cambridge- use of clean room via Patrick See and provision of wafer materials. UCL - EPSRC CASE student with Prof Sir Michael Pepper. Royal Holloway - joint PhD student Simon Schmidlin until May 2012. Leeds University – EPSRC CASE student with Prof John Cunningham.

Deliverables

1	**Start: 01/04/13**	**End: 30/12/14**	**Cost:**
Deliverable title: Investigation of the physics behind the electron pump mechanisms Evidence: Published experimental results.			
2	**Start: 01/01/15**	**End: 30/06/16**	**Cost:**
Deliverable title: Determination of the current plateau flatness at a level of 1×10^{-7}. Evidence: Published experimental results.			

Project No.	EMT 13013	Price to NMO	£176k
Project Title	**Cofunding for EMRP Project MICROPHOTON EXL03**	Co-funding target	£135k in place
Lead Scientist	Masaya Kataoka/Tobias Lindstrom	Stage Start Date	1/07/13
Scientist Team	JT Janssen, Alexander Tzalenchuk, Patrick See, Stephen Giblin, Jonathan Fletcher	Stage End Date	30/6/16
		Est Final Stage End Date	

Summary

The lack of emitters and detectors capable of operating at the single-photon level at microwave frequencies is the bottleneck for progress in many areas of quantum technologies, including quantum information processing and communication (QIPC) and quantum metrology, and also in the development of cryoelectronic devices. The main objective of this project is to develop single-photon microwave emitter/detector technology that can be practically used in daily operations.

The Need

Unlike at optical frequencies, there are no detectors that can reliable resolve single photon events at microwave frequencies. This has been a major issue for QIPC based on circuit quantum electrodynamics (cQED) and for testing cryonanoelectronic quantum devices that are sensitive to the detrimental effect of residual microwave photons. In QIPC, the quantum information in solid-state “static” qubits can be transferred onto single-microwave-photon “flying” qubits to create a quantum communication bus. The development of any future superconducting quantum computing technology will necessarily depend on the availability of on-chip single-photon and few-photon microwave components. Amplifier development for wireless communications and radiation metrology would greatly benefit from ultra-low-signal sources and ultra-sensitive detectors. There is also a very urgent need for microwave photon detectors in characterising and minimising the background microwave radiation in cryogenic environments, in order to improve the performance of several quantum devices. There are world-wide efforts by academic and industrial institutes in these areas with high expectation both in scientific and economic outputs. Governmental support would greatly benefit the academic and industrial research in UK.

The Solution

We will develop critical technologies for creating, detecting and eliminating microwave radiation at the single-photon level. In order to cover the full range of microwave frequencies (3 – 300 GHz), we will employ various device technologies (e.g. Josephson devices, superconductor-insulator-normal-insulator-superconductor (SINIS) junctions, and semiconductor quantum dots) that the different consortium participants have extensive experience with. We will the use these detectors and emitters for characterising cryogenic systems in order to build an ultra-quiet microwave environment.

Project Description (including summary of technical work)

This project consists of 4 NMI partners (NPL, MIKES, PTB, INRiM) and 3 academic REG partners (Aalto, Lancaster, Royal Holloway), and addresses the following scientific and technical objectives (NPL is involved in **01** and **02**):

01: Development of single-microwave-photon detectors which give spectral information of radiation. Sensors will be developed to cover a wide frequency range from below 10 GHz up to about 300 GHz. The methods will be based on superconductor and semiconductor nanodevice technologies.

02: Development of cryogenic sources of microwave photons to cover frequencies between 4 GHz and 300 GHz – a single-photon source based on a superconducting qubit, and other microwave photon sources based on biased Josephson junctions and on black-body radiation – and their use in characterization of the developed photon detectors.

03: Characterization and minimization of background microwave radiation in cryogenic measurement systems of nanoelectronic devices. The goal is to decrease the background microwave radiation to a level which corresponds to voltage noise of a SINIS-SET (single-electron transistor) much below 1 $pV/Hz^{1/2}$ at frequencies above 10 GHz, simultaneously allowing bandwidth up to about 10 GHz for controlling signals from room temperature to the cryo-electronic device.

04: Demonstrations of improved performance of cryoelectronic quantum nanodevices such as SINIS-SET-based components and other devices in which perfectness of superconductivity is important.

Impact and Benefits

This project is aimed at making a substantial scientific impact, realising for the first time practical single-microwave-photon detectors and sources. This breakthrough will eliminate a barrier that is impeding the progress on the emerging field of quantum device technologies. It will also lead to novel electromagnetic metrology for microwave frequencies at very small signal levels, ultimately at the level of single photons. According to a recent report, the European Union is funding research in the field of quantum information and communication by about 15 M€/year, and in the U.S. the national funding for QIPC is about 60 M€/year. This project gives an excellent opportunity to disseminate the unique and very relevant know-how of metrologists into this field of remarkable scientific, economic and public interest.

Support for Programme Challenge, Roadmaps, Government Strategies

This project addresses the following challenges identified in the EMRP Outline 2008: "Development of ultra-sensitive characterisation methods for nano-structured devices and materials" (page 32), "Electricity and Magnetism: Development of ultra-sensitive measurement tools allowing the characterisation of nanostructured materials, components and systems used in tomorrows' nanoelectronics and nanomagnetics technology" (page 11), and "New technologies ….In many cases in nanotechnology, quantum mechanical effects prohibit a scaling-down of the properties of micro systems and thus require new scientific approaches…research underpinning quantum cryptography…" (page 9). This project is also in line with the recent TSB Information Security roadmap, which identified quantum computing and the development of new communication protocols among a few disruptive technologies, which may radically change information security landscape over the next decade.

Synergies with other projects / programmes

The methodologies of low-temperature refrigeration, and low-noise/RF electrical measurements are shared with at least five other projects in the NMS programme. The research subjects of this project are closely linked with the NMS Quantum Current Standard and Solid-State QIP projects.

Risks

This challenging project relies on extensive collaboration with NMI and REG partners, and there is a moderate risk that the final deliverables are not achieved due to failure in one of the tasks. There are various mitigation plans in place to minimise this risk (e.g. fabrication or measurement activities can be transferred to other partners).

Knowledge Transfer and Exploitation

The outcome of this project is mainly disseminated by scientific papers and presentations aimed at both technical and general audiences. The project results would be targeted at journals on the level of Nature/Science.

Co-funding and Collaborators

This project is cofunded by the EMRP and lead by MIKES. Other partners are PTB, INRIM, Aalto, Lancaster University and Royal Holloway College.

Deliverables

1	**Start: 1/7/13**	**End: 30/6/16**	**Cost:**

Deliverable title: Cofunding for EMRP Project MICROPHOTON

Project No.	EMT 13014	**Price to NMO**	£305k
Project Title	**Co-funding for EMRP (Quantum Engineered States for Atomic Sensors Including Optical Clocks)**	**Co-funding target**	£238k (EMRP)
Lead Scientist	Guido Wilpers	**Start Date**	01/07/2013
Scientist Team	Guido Wilpers, Alastair Sinclair, Joseph Thom	**End Date**	30/06/2016

Summary

To explore quantum-mechanical entanglement in scalable trapped-ion systems for quantum-enhanced sensors, and to overcome present limitations in optical clock performance. To develop the techniques to control quantum entangled states in a scalable system based on our microfabricated ion trap processor chip. To demonstrate interferometric phase-sensitivities beyond the standard quantum limit and design entangled systems based on multiple ion quantum bits (qubits).

The Need

Quantum sensors based on atomic quantum bits (qubits) offer the potential to achieve unprecedented levels of measurement sensitivity, e.g. in frequency metrology, gravimetry and magnetometry. Reaching their full potential is hampered by the control of systematic uncertainties, and by instabilities enforced by the standard quantum limit. The use of N entangled ion qubits enables the improvement of stability that scales linearly with N rather than $\sqrt{N}$, and enables the Heisenberg uncertainty limit to be reached. Achieving this in a scalable system offers a route to a major advance beyond the standard quantum limit. In a single-ion device, measurement uncertainties of 10^{-18} are envisaged, but in the ideal case, realisation of this target will necessitate 2 weeks of continuous measurement. In comparison, a future device based on 10 entangled ions could ideally reach the same result in 3 hours, i.e. 100 times faster. Furthermore, entangled states can also be used to cancel systematic effects intrinsically. At present this can only be achieved by explicit measurement and subsequent correction.

Quantum entanglement of ions, and their application to metrology, was pioneered by groups at NIST and Univ. Innsbruck. State of the art includes:

- NIST, Boulder: entanglement of 6 ions (microwave qubits) in a non-scalable 3D ion trap. Operate scalable surface ion traps.
- Univ. Innsbruck: entanglement of 8 ions (optical qubits) in a single segment macroscopic ion trap.
- NPL: development and operation of a scalable monolithic 3D ion trap. Measured trap characteristics show the device is highly suited to entanglement (Nature Nanotechnology, Sept 2012).

This project supports the development of atomic quantum technologies, such as sensors, clocks and quantum information processing. Quantum metrology is an important enabler for these applications, and commercialisation of them is a major opportunity for the UK science base, hence the need for government support .

The Solution

To demonstrate entanglement of trapped-ion qubits in a scalable device, whilst maintaining the precise nanoscale control typical of single-ion systems. The system needs to exhibit high fidelity multi-particle entanglement, where quantum coherence is minimally influenced by the trap environment.

Project Description (including summary of technical work)

The project will be carried out using an improved design of microtrap chip. Each component for quantum state control will be developed in a step-wise fashion. Firstly, an ion string will be cooled to the motional ground state, thus initialising the qubit register. Stabilising the magnetic field is required to reduce decoherence, and is necessary for demonstrating a 2-qubit entangling gate. Investigation of quantum state coherence during transport is necessary to assess prospects for scaling to larger entangled states. A 4-ion entangled state will show an increased spectral sensitivity in an interferometric experiment.

Impact and Benefits

Primary impact and benefits are scientific value and measurement capability. The project seeks to capitalise on the NPL's world-leading ion trap microchip for quantum technologies: "A monolithic array of three dimensional ion traps fabricated with conventional semiconductor technology", *Nature Nanotechnology*, advance online publication, DOI: 10.1038/NNANO.2012.126 (2012). Two other manuscripts have arisen from this work; one has been submitted to Applied Physics B, the other to IEEE Journal of Microelectromechanical Systems. Future impact of this work will be in:

- Improved precision for optical frequency metrology, contributing to EU NMI expertise in entanglement enhanced spectroscopy.

- Techniques for entanglement-enhanced quantum sensors.
- Benefits to navigation (GLONASS, time keeping), relativistic geodesy, astronomy (transition wavelength), fundamental physics (drift of fundamental constants).
- ESA future generation frequency metrology and time keeping for navigation, relativistic geodesy and research into relativity.
- Metrics for ion trap processor chips for quantum technologies.

Support for Programme Challenge, Roadmaps, Government Strategies

This proposal supports the NMS strategy as follows:

- "to retain a leadership position in selected areas of science", specifically "quantum technology including optical clocks"
- "participation ... … … in collaborative projects with European national measurement institutes in the European Metrology Research Programme"
- "engaging … … … graduates through Research Council programmes and Engineering Doctorates" and "hosting high quality visiting researchers on secondments"
- This project supports the Roadmap entitled "Atomic Clocks and Frequency Standards for Time & Frequency Metrology", specifically on multi-ion clock architectures, dual ion spectroscopy, quantum logic clock, entanglement-aided clocks, compact optical clocks for space applications.

Synergies with other projects / programmes

The proposal complements existing research on single-ion frequency standards by researching quantum methods for improved stability. The techniques and capability for quantum state manipulation and readout that will be developed are of direct relevance to existing research on ion strings for quantum logic spectroscopy. The future plan is to scale up to many ($N \geq 10$) particle entangled states to realise a worthwhile gain in sensitivity over single or uncorrelated systems.

Risks

The greatest risks are associated with the technical development of microfabricated ion trap chips, and maintaining operation of a suitable device. A new fabrication run is planned, correcting the deficiencies of the first operational device.

Knowledge Transfer and Exploitation

Dissemination of results will be via 1) presentations to national and international workshops and conferences, 2) Publications in peer-reviewed scientific journals. In the near term, primary beneficiaries are in the scientific and metrology communities, specifically for developments in quantum sensors & frequency standards, and quantum information processors. In the medium term, the technology is attractive to the defence and space sectors. Presently, DSTL is investing in quantum sensors (DSTL call 2011) and quantum processors (Centre for Defence Enterprise call 2012). ESA have invested in various forms of atomic sensors and clocks over the past decade, and are now funding related development work for microfabricated atom chips.

Co-funding and Collaborators

EMRP: open excellence SRT-x06 "Quantum engineered states for optical clocks and atomic sensors". Collaborators are SYRTE (lead) and PTB. Total value ~300k Euro to NPL.

EPSRC: Engineering Doctorate Centre in Optics and Photonics Technologies. 4-year studentship collaboration with Univ. Strathclyde. Funded 2010-2014.

3rd Party opportunity: Centre for Defence Enterprise call on Future Digital Systems (Q4 2012). Value up to ~£70k for ~9 month proof of principle project. Success probability ~65%

Deliverables

1	**Start: 01/07/2013**	**End: 30/06/2016**	**Cost:**

Deliverable title: Co-funding for EMRP Project EXL01 Quantum Engineered states
Evidence: As outlined in the EMRP project

Project No.	EMT 13015	Price to NMO	£178k
Project Title	**Co-funding for EMRP SIQUTE EXL02 Single-Photon Sources for Quantum Technologies**	Co-funding target	£139k
Lead Scientist	Alastair Sinclair, Jessica Cheung	Stage Start Date	01/07/2013
Scientist Team	Christopher Chunnilall, Raj Patel	Stage End Date	30/06/2016

Summary The aim of this proposal is to develop new single-photon sources for the purposes of quantum optical technologies. Currently no true single-photon source exists that can emit N photons on demand – such a source would enhance quantum communications and developments towards quantum computers which will need quantum photonic networks. NPL will work with other NMIs and the lead academic groups in this area to develop true single-photon sources, assess those sources using the single-photon metrics facility developed at NPL according to appropriate metrics in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability. We will also demonstrate the suitability of these sources for different entanglement enhanced measurements based on those metrics.

The Need Single-photon sources are necessary for quantum information processing. To exploit such sources we need optimum coupling efficiencies and complete characterisation of the sources to assess their suitability for QIP type experiments such as entanglement. This research will help build the foundations required to take QIP experiments out of the lab and in to industry for the next generation of computers (quantum computers) and data security (quantum key distribution) and metrology (quantum enhanced measurements and quantum radiometry).

The Solution

- Development of absolute, calculable single-photon sources with a photon flux up to 10^7 photons/s based on quantum dots and vacancies in nano-diamond technologies and heralded single-photon sources
- Characterisation of these sources via appropriate metrics e.g. wavelength, bandwidth, photon statistics, anti-bunching. NPL is the only NMI to have a complete set of measurement capabilities in house that have already been developed
- Assess suitability of sources for different applications based on those metrics (NPL)
- Optimisation of photon collection efficiencies

Project Description (including summary of technical work) The project will develop highly efficient, electrically pumped and compact single-photon sources with photon fluxes of up to $10^{\&}$ photons per second, with near unity collection efficiency based on semiconductor quantum dots. This requires using molecular beam epitaxy (MBE) to fabricate InAs/GaAs quantum dots (QD) emitting in the spectral range between 900 nm and 950 nm, the design of the appropriate structure to realize near unity collection efficiency for optically and electrically pumping with the help of numerical modelling, and characterization with respect to photon rate, g(2)-value, photon statistics, and spectral and temporal characteristics. Heralded single-photon sources operating in the telecom band will also be developed. The sources will be developed by academics and characterised by NPL.

The project will provide new sources of quantum optical states with non-classical state correlations that will improve the accuracy and the sensitivity of measurements beyond the standard quantum limit (SQL), also referred to as the shot noise limit (SNL). The most suitable of the single-photon sources developed that satisfy the requirements for creating non-classical correlations will be used to create these states. The degree of measurement enhancement produced by using these states will be quantified, and the consequences for other quantum enhanced measurement (QEM) schemes assessed. To achieve this there are two challenging tasks. The first is to devise and implement an optical system for achieving quantum enhanced measurement. This system needs to be such that the performance of the measurement can be quantified, and related back to the quantified properties of the input photons and the experimental set-up. The second is the significant challenge of entangling photons from deterministic single-photon sources. Issues that must be overcome include source and detector jitter, de-phasing and bandwidth mismatch between photons.

Impact and Benefits

Innovation and Measurement

What benefits will result from this work and how will their impact be measured? This section should include evidence, when relevant, about the project's impact on the economy (short term, 1 – 5 years), quality of life, and innovation, as well as the project's scientific value and its contribution to developing or maintaining the NMI's measurement capability.

Quantum information processing: quantum random number generation, QKD and photon based quantum computation rely on close to perfect single-photon sources. A true single-photon source will remove the key vulnerability of current QKD systems where attenuated lasers can lead to multi-photon eavesdropping attacks. Validated measurement techniques will allow us to determine suitability of source for applications such as entanglement. This research works towards real implementation beyond the scope of this project therefore the impact will be evident once the first practical QKD system is demonstrated with a validated single-photon source. All scientific fields reliant on photon detection devices such as biology, medical imaging, astronomy, quantum optics can benefit from the existence of an easy to use photon standard.

Social impact - The secure transmission of information and the protection of privacy of individuals gain more and more importance for the data traffic at public institutions and for strengthening and maintaining the competitiveness of the European economy. The "naturally" tap-proof quantum cryptography is increasingly seen by politics and economics as one way, to obtain secure data transmission in real life. In the ongoing development and use of digital technologies in many areas of our daily life, data privacy protection is steadily gaining importance for society, see e.g. bank transactions, customer profiling in the field of marketing or for the protection of employee data. QKD systems are considered as key technologies to protect the right to privacy in the processing of personal data, and single-photon sources developed in this JRP are key foundations for its realization.

Financial impact-. In Europe, the companies IDQuantique, Switzerland and Toshiba, UK are the leaders in the field of commercial QKD systems. Today, attenuated laser beams are used; with highly efficient, high quality single-photon sources higher key transmission rates and thus higher customer acceptance for such systems will the realized. Furthermore, single-photon sources may also play a significant role for quantum number generators (i.e. lotteries) as well as for producers of school and academic experimental setups. The exact numbers are difficult to quantify, however, the market prospects cannot be underestimated.

Support for Programme Challenge, Roadmaps, Government Strategies

1. NMS Strategy 2012: the digital challenge and the security challenge
   - Digital Challenge, NMO will, through the NMS programmes: "*Develop measurement methods to underpin the specification and reliability of the technology for next generation communication systems*."
   - Security Challenge, NMO will, through the NMS programmes: "*Provide standards and measurement methodologies to support the security of citizens, infrastructure and utilities, intelligent surveillance and border and data security, and the maintenance and development of defence capabilities*."
2. External roadmaps (Photonics21, 2011; EURAMET Basic Science Roadmap 2012)
3. TSB Grand challenges – digital security
4. Q-TAP Quantum – Technologies review
   - 'UK based Quantum Secure Communications commercial demonstration test bed /sand-pit for the development and testing of applications and accreditation of turn-key systems'
   - 'UK is lagging behind other countries despite its knowledge base – as a direct result of lack of funding'

Synergies with other projects / programmes The activities of this project draw on existing facilities and expertise developed in pathfinder and physical programmes. A current programme on metrology for quantum key distribution aims at developing a complete measurement infrastructure for the characterisation of the disruptive technology, Quantum Key Distribution. QKD currently relies on sources that are highly attenuated lasers. A true single-photonsource however will be far less vulnerable to attack and is likely to be implemented in next generation QKD devices – if a suitable source can be developed and characterised. The knowledge gathered here adds to the foundations of QIP metrology and can be developed further along with other R&D developments that are still very much lab-based activities (quantum repeaters, quantum memories, quantum computing)

Risks The technical risk is that no single-photon source is assessed to be suitable to carry out quantum enhanced measurements. In this case we will continue with heralded single-photon sources which have been successfully implemented in many experiments to demonstrate quantum effects.

Knowledge Transfer and Exploitation Dissemination will be through publications in high impact factor journals and presentations at key conferences such as Single photon workshop (Los Alamos National Labs, USA, October 2013; GAP Optique, Switzerland, 2015) and Quantum 2014 and Quantum 2016, INRIM, Italy.

Co-funding and Collaborators This project is linked with the EMRP proposal: Single-photon sources for Quantum Technologies Activities within this project will be carried out in partnership with other NMIs, namely INRIM, PTB, CMI, METROSERT and MIKES and also other academics, CEA Grenoble, France; University of Saarlandes, Germany; DTU Fotonik, Denmark; Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany.

Deliverables

1	**Start: 01/07/13**	**End: 30/06/16**	**Cost:**

Deliverable title: Co-funding for EMRP SIQUTE EXL02

Project No.	EMT 13016	Price to NMO	£263k
Project Title	**Co-funding for EMRP SpinCal EXL04**	Co-funding target	£200k in place
Lead Scientist	Olga Kazakova	Start Date	01/07/2013
Scientist Team	David Cox, Hector Corté, Jonathan Fletcher	End Date	30/06/2016

Summary Domain Wall devices are being developed by many leading European and international research groups and they require advanced metrology to perform the necessary characterisation, calibration and standardization that enable these devices to be optimised and commercialised. This includes traceable methods to reliably measure the nucleation and propagation fields and currents, to determine the sensitivity of DW devices to additional small magnetic fields (*e.g*. produced by a single bead), to measure any offsets that are present, and to establish key parameters such as the gain and linearity with a low known uncertainty. It is necessary to establish facilities that can calibrate the key quantities with an uncertainty that is at least an order of magnitude better than that required for potential industrial application. This project aims to develop the capability and infrastructure to make traceable measurements using the expertise of the EMRP Spincal project partners to establish these world leading facilities. NPL is the leader of the work package in the EMRP project.

The Need The increase in uptake of magnetic sensors is indicated by a revenue growth rate of ~10%/year stimulated by increased usage of magnetic sensors in cell phones and other consumer electronics as well as the automotive industry drive for sensor systems that improve fuel efficiency and safety. Biomedical nanosensors is a new, rapidly developing area. This expanding market is fed by a desire for innovation in device performance which can only be met by technical developments in materials and the use of novel magnetic concepts. A lack of suitable nanomagnetism measurement tools is hampering the progress of companies trying to develop potential mass-market products. The value of the Nanomagnetism project is, thus, associated with the development of magnetic measurement techniques and materials at the frontier of current technical capabilities in Europe and worldwide. This project provides the the next generation of traceable metrology techniques that are essential to accelerate innovation.

The Solution The proposed project will provide the metrology to characterise next generation of devices (e.g., nano-Hall and domain wall) traceable to the existing standards. Moreover, at the 1st time the 3D quantitative sensitivity mapping with nanoscale resolution for these sensors will be delivered. This approach promises a significant stepwise improvement compared to the current state of the art and will eventually help to solve problems associated with measurements of small magnetic moments and allow a significant breakthrough in miniaturization of commercial products. To enable this challenging task we have already developed major measurement capability and established the external fabrication routes. The results will be validated and compared by exchanging samples with companies and other NMls.

Project Description (including summary of technical work) The key outcomes of the project will be:
Within this project we will develop, realise, and investigate magnetic nanodevices made of Perpendicular Magnetic Anisotropy (PMA) materials allowing the detection, manipulation, and control of individual DWs. The main advantages of PMA materials include narrow DWs (< 10 nm) with a simpler and more rigid internal Bloch/Neel DW structure; high non-adiabaticity effects due to the high magnetization gradients and high spin–orbit coupling leading to low critical current densities and high velocities. in combination with a small DW width it provides, e.g. a small size of the magnetic bit for high density magnetic memories as well as low energy consumption and significantly improved reliability of spintronic devices. The two main metrology tasks to be carried out are:

Task 1: Experimental metrological setup for magnetic domain wall devices

The aim of this task is to establish a metrology setup for the measurement of magnetic DW nucleation and propagation in magnetic nanowires with PMA. This task will initially (within the first 6 months) establish the scope of the measurement requirements (magnetic field, spin current, temperature stability, measurement uncertainties) through widespread consultation with REG partners and external stakeholders. It will then implement experimental methods to perform the identified calibrations while precisely controlling the magnetic environment and maintaining the chosen parameters. Within this task a room-temperature experimental system based, *e.g*. on a solenoid approach, will be built up, extensively tested and calibrated at NPL

Task 2: Towards metrology based on magnetic domain wall devices

The aim of this task is to explore magnetic bead detection based on magnetic DW devices with perpendicular anisotropy. These devices will be decorated by magnetic beads using either a nano manipulator in a scanning electron microscope (SEM) or by atomic force microscope (AFM) based manipulation. The DW propagation of bead decorated devices will be compared to that in empty control devices. Potential of such devices towards individual bead detection will be compared to performance of similar devices made of soft magnetic materials.[i] The magnetotransport response of the DW devices in the presence of a magnetic bead will be evaluated with respect to bio-applications. Also the prospect of a future manipulation of magnetic beads immersed in liquids by a propagating DW will be evaluated.

Impact and Benefits

The main impact associated with the project will be in the development of i) smaller and more sensitive, in particular in ambient environment, magnetic sensors; traceable and precise calibration and optimization of their performance, i.e. compensation of the parasitic electrical effect and maximization of the sensing area; ii) quantitative combined magnetic and electrical microscopy and iii) novel nanodevices (e.g. sensors and logic) based on DWs in materials with PMA. All these products are generally not commercially available. The impact will be achieved through knowledge transfer, new services, demonstration of initial prototypes and in a longer term their transfer to industry. We are potentially seeking for patenting of the method for calibration of magnetic probes. Successful realization of the project will benefit the following industries and markets:

- well-established information technologies (i.e. computer memories, logic, MRAM, spin-transistors);
- emerging - energy harvesting, environmental protection and monitoring (i.e. magnetic refrigeration, chemical sensing).

Support for Programme Challenge, Roadmaps, Government Strategies Support for Government Strategies

The project supports the aim of the NMS strategy “The NMS laboratories will lead the development of characterisation tools, methodologies and reference materials for nanomaterials to facilitate their application and to underpin environmental, health and safety research”. Nanotechnologies are widely predicted to become the main driving force supporting economic growth in the 21st century. UK Government White Paper" identifies nanotechnology as a vital new and innovative area capable of creating new products and industries. The Royal Society report - 'Nanoscience and nanotechnologies: opportunities and uncertainties' highlights the importance of metrology to underpin nanoscience and nanotechnologies and the need for standardisation of measurement on the nanometre scale required by regulators and industry.

Synergies with other projects / programmes

This project further develops the expertise from the completed project ‘EMT12 114503 Nanomagnetism’

Risks The main risk is associated with manpower. We are seeking to get a full time researcher (PhD student or post-doc) and several part-time students working on the project.

Knowledge Transfer and Exploitation

Knowledge transfer will be achieved using a variety of routes including;

- New science (publications in Phys. Rev. B, NanoLett, Nanotechnology, etc. and conference presentations - Intermag, MMM, MRS, IEEE Nano).
- Incoming/outcoming secondments, e.g. to other NMls, academy and industry.
- Discussions with industrial partners and participation in their roadmapping.
- Intellectual Property (patents, licenses).
- Possibility to offer prototypes of devices to industry. Joint publications with industrial partners.
- Dissemination agreement with DFG Priority Program Spin-caloric transport

Co-funding and Collaborators The project is cofunded by the EMRP programme with the following collaborators,University of Regensburg, Ohio State University,Techn. University of Kaiserslautern, University of Alabama, Max-Planck-Insitut for Chemical Physics of Solids, Tohoku University, International Business Machines Corporation, Research Division,Singulus Nanodeposition AG,Hitachi Cambridge Research Laboratory, Durham Magneto Optics Ltd

Deliverables

1	**Start:** 01/07/2013	**End:** 30/06/2016	**Cost:**

Deliverable title: Co-funding for current EMRP project Spincal EXL04

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Technical Theme

Electromagnetic Metrology

Science Area Leader

David Humphreys & Richard Dudley

Project No.	EMT 13017	Price to NMO	£607,500
Project Title	**RFMW and Ultra fast Capabilities Support**	Co-funding target	
Lead Scientist	N/A	Start Date	01/04/2013
Scientist Team	Measurement Service Team	End Date	31/12/2013

Summary

To provide the facilities, capability and expertise necessary to disseminate RF, Microwave and Ultra-fast Core measurements to industry, through the provision of measurement services, consultancies and support to R&D. To ensure these measurement standards are harmonised with those of the UK's trading partners through intercomparisons, ensuring mutual recognition.

The Need

This project supports the fundamental infrastructure, facilities and expertise to deliver the traceable measurement services to industry required by the NMS strategy and directly supports the R&D projects in the Electromagnetic and Time Programme.

To be competitive in a global market, every nation must ensure its industry has access to suitable measurement standards, in which there is universal confidence. In most cases, these standards are provided by UKAS accredited calibration and test houses, however these require traceability to national standards that are coordinated with those of our trading partners. Through participation in international comparisons, systematic errors can be identified, addressed and confidence maintained.

A comparison of Calibration Measurement Capabilities (CMCs) can be made by accessing the BIPM CMC database here: http://kcdb.bipm.org/appendixC/default.asp. Also NPL's performance in intercomparisons can be viewed in the Key Comparison Database here: http://kcdb.bipm.org/default.asp.

The Solution

1. Ensure that the necessary facilities and expertise are available to provide the wide range of relevant measurement services to industry to underpin UK innovation and competitiveness.
2. Participate in intercomparisons to ensure international acceptance of the NMS capabilities.
3. Incorporate new capabilities , e.g smart antennas, future satellite based systems and imaging, high speed electronics .

Project Description

This project is concerned with maintaining the facilities and expertise necessary to deliver the 17 separate measurement services in the RF, microwave and ultra-fast pulse area.

The technical work would include:

- Calibrate, verify, service and repair all relevant equipment and facilities to maintain capability and infrastructure necessary for the delivery of our measurement services, both externally and internally.
- Demonstrate capability nationally, through UKAS and LRQA audits, and internationally through peer review of CIPM Calibration Measurement Capabilities.
- Safeguard UK interests by scrutinizing CMC claims made by other NMIs to ensure the validity of calibration certificates issued through the Mutual Recognition Arrangement.
- Coordinate UK electrical traceability with that of other countries through participation in, and piloting of, EURAMET and CCEM international comparisons.
- Provide traceability for RFMW electrical standards to UKAS and other laboratories through provision of the measurement services underpinned by the project.
- Provide access to facilities and expertise through measurement consultancies.
- Keep staff expertise up-to-date through workshops, conferences and standards.
- Where not covered by other, more specific project, provide input to standards

Impact and Benefits

1124 certificates issued to industry per year. Traceability provided to UKAS labs, providing very significant fan-out. Confidence in measurement through traceability to SI units, internationally peer reviewed through the CIPM MRA. Wide range of consultancy work undertaken, for example assessing the performance of GPS antennas for geodetic surveying. To enable industry to develop new innovative products and ensure they meet current standards.

Support for Programme Challenge, Roadmaps, Government Strategies
The RF and MW facilities, expertise and services underpin the following strategic areas as outlined in the NMS strategy: Traceable Metrology and UKAS – "Ensure calibration and testing laboratories are adequately supported by the
NMS infrastructure through the provision of traceable measurement standards", "provide world class statutory and commercial measurement services". This project also supports the following challenges of the NMS strategy "Provide the infrastructure for next generation communications systems, such as smart grids, tele-healthcare and environmental monitoring" and maintain "accurate measurement essential for assuring consumer protection… and safety… and legislation". It will also support the NMS digital agenda by maintaining services to overcome "measurement challenges to the industry requiring higher speed instrumentation, higher performance antennas….".

Synergies with other projects / programmes
This project will provide some of the basic infrastructure and traceability required for projects in the following areas:
1) High speed electronics – printed circuit boards and linear active devices
2) Waveguides for millimetre and sub-millimetre wavelengths
3) Primary measurement systems for electronic component characterization at millimetre wave frequencies
4) Advanced antenna metrology
5) Complex waveforms and large-signal RF metrology
6) Health and Exposure (SAR)

Risks
On the whole the risks relating to this project are low, given the facilities and expertise are in existence. In addition, an essential element of the project is concerned with solving unanticipated problems with the facilities as they arise, therefore there is an in-built risk mitigation mechanism. Remaining risks are:
1) Loss of key staff
2) Significant problems with the building that are outside our immediate control, in particular the temperature control.

The nature of this project is such that it tends to mitigate risks on other projects by ensuring the underlying infrastructure and expertise are operational and available.

Knowledge Transfer and Exploitation
The key method for knowledge transfer is through the provision of measurement services to industry and the advice provided to end-users to ensure the measurements offered meet their needs. In addition:
- Presentations/papers at workshops and conferences
- Updates to the Measurement Services pages on the NPL website, providing technical information
- Articles for NPL Newsletters
- Dissemination of information to user groups, for example ANAMET and the mm-wave User Group
- Reviewing papers for journals
- Participation in training courses
- Visits to industrial customers to understand their present and future technical needs

Co-funding and Collaborators
£1.34m revenue per year from industry from measurement services alone shows the value of the work to the sectors involved. In addition the project enables traceable measurement to be deliver to collaborators and stakeholders in TSB and EMRP projects.

Deliverables

1	**Start: 01/04/2013**	**End: 31/12/2013**	**Cost:**

Deliverable title: RFMW Free-Field Facilities and Infrastructure
Provide traceability for Free-Field quantities to industry through the provision of measurement services.
Demonstrate ongoing expertise through UKAS/LRQA assessments and participation in intercomparisons.

Project No.	EMT 13018	Price to NMO	£440k
Project Title	**Electromagnetic Metrology for a Faster World**	Co-funding target	
Project Lead	David Humphreys	Start Date	01/01/2013
Project Team	Nick Ridler, David Humphreys, Irshaad Fatadin, Richard Dudley, Mira Naftaly, Rob Ferguson, Martin Salter, Matthew Harper	End Date	30/12/2015

Summary
Advances in electronic and photonic components and systems, driven by the International Technology Roadmap for Semiconductors, have introduced new measurement quantities that have poor traceability to SI units. This project will to provide this traceability, covering a number of different high-bandwidth technologies with a unifying theme of waveform metrology. There are opportunities for different types of high-quality science and technology output and different types of impact matched to the level of technological maturity across the project.

The Need
The current state-of-the-art for high-frequency electronics applications has brought about a new generation of test equipment and also impacts the communications infrastructure through increased demands for bandwidth. The issues addressed in this project and the related EMRP project are:

Application	Measurement need
Lack of traceability to SI for high-frequency components and instrumentation presents a barrier to adoption.	1: Traceable measurement capabilities in coaxial line and waveguide 50 GHz to 1100 GHz.
Qualitative measurement techniques, such as 'eye-diagrams' cannot be used for fault location.	2: Develop traceability for multi-port network analyser and time-domain differential measurements on coaxial and planar lines on microwave substrates and PCBs.
Confidence in the large-signal measurement accuracy between systems required for development of Energy-efficient RF components.	3: Develop traceable calibration artefacts to support metrology for active devices – Nonlinear, large-signal measurement.
Development of new components and technology for high-bandwidth short-range THz communications.	4: New metrology is needed to support THz component technology development.
Core optical communications network (100 Gbit/ sec/ channel) project increase of x4 to x10 during project life.	5: Metrology to support component and instrumentation development for advanced optical modulation formats.

The Solution
The project activities reflect the measurement needs. All work will be carried out with industry (I), academic (A) or NMI/EMRP (E) collaborators.

1. Extend frequency range and verify with collaborators. Measurement evidence for international standards (E, A, I).
2. Provide robust assessment of single port and multi-port calibration on balanced and unbalanced lines (E, I).
3. Work closely with K U Leuven to develop and verify a theoretical design and practical standards artefact (A, E).
4. Collaborate with several institutions to access devices. Use existing expertise on wireless communication waveforms and parameter (EVM) to develop traceable measurement support (A).
5. Measurement capability for xPSK and QAM modulation. Assess instrument architecture and impairment (E, I).

Project Description
Develop and disseminate basic metrology science and new advanced techniques to research community and industry. The level of technological maturity differs across the tasks but there is a common traceable broadband waveform measurement theme. Opportunities for significant new science exist in all these areas.

1: Develop underpinning metrology to support technology development for emerging Terahertz Communications & Networks. The work focuses on the methods to characterize the performance of free-space devices and systems operating, in the frequency range of 0.3-3 THz. In addition, the channel, modulation schemes and parametric measures such as Error Vector Magnitude (EVM) and eye diagrams will be investigated.
2: Develop traceable coherent detection test methods to quantitatively evaluate the complex modulation and diagnose faults in high-speed optical transmitters from constellation diagram analysis. EVM will be used to characterize imperfections in the transmitter and to understand key parameters affecting system performance.

3: Develop traceable S-parameter measurement capabilities in coaxial line, concentrating on the 1.85 mm line size, and waveguide 50 GHz to 1100 GHz. Initial work in waveguide will cover frequencies up to 220 GHz, which will be extended to at least two bands in the 110 GHz to 1100 GHz region and later contribute to two international standards development. In addition traceability for differential S-parameter measurement of planar circuits, including on-wafer and high-speed Printed Circuit Boards (PCBs), will be investigated later in this project.

Impact and Benefits

1: Strategic: NPL will gain facilities and expertise to lead these technologies at an international level. Maintain NPL's position as a focal point for these technologies.
2: Commercial: The work in this project will enable customers and suppliers of devices and systems to offer assured products due to defensible specifications that are backed-up by measurement traceability chains.
3: Knowledge: Much of the impact delivery is through knowledge transfer by publications and contribution to international standardisation. Expertise supports UK industry and academia.

Support for Programme Challenge, Roadmaps, Government Strategies

The project aligns with the NMS 'Digital Economy' Strategy "Providing the infrastructure for next generation communications systems" and the 2020 Digital Agenda for Europe, identified as a prerequisite for Growth; High-bandwidth systems support Energy agendas by reduced Operational expenditure; The International Technology Roadmap for Semiconductors (www.itrs.org) and projected the trends for optical communications at OFC 2012, IEEE 802.3 HSE Consensus Ad Hoc and EPSRC Research priorities (RF/Optical).

Synergies with other projects / programmes

The project builds on concurrent projects and the NPL knowledge base:
1: EMRP IND 16 Uncertainty analysis techniques for dynamic waveforms.
2: EMT 13022 [Space]: Millimetric and THz RF power standards provide fundamental underpinning.
3: EMT 13020 [Real-World]: This work supports UWB Antenna characterisation and ad-hoc RF environments.
Note the EMRP SIB 61 (HF-CIRCUIT) project was successful and a significant part of the planned work in this project has been moved into a separate co-funding project to support that work which starts in July 2013

Risks

1: External influence and activities not under NPL control, e.g. progress of standards bodies, changes to the research direction of key academic and industrial collaborators. Mitigate by alternative collaborative links/ task re-scheduling.
2: The risk factor for the THz work is the level of maturity of the technologies which can be mitigated by working with more than one institution. The technical risks associated with developing a reference standard or capability is that different types of devices will require different measurement methodologies and equipment.

Knowledge Transfer and Exploitation

The main technology transfer is through International peer reviewed publication, e.g. IEEE Trans. or Letts. papers and IEEE Explore searchable conferences (>18 papers expected in this and related EMRP project). Local technology exchange through groups such as ANAMET (NPL) and ICTKTN and the use of new media opportunities as appropriate. Some work will result in measurement services or calibration transfer artefacts to closely support industry. Explore viable IP opportunities.

Co-funding and Collaborators

The related EMRP SIB 61 project has numerous NMI, industry and academic collaborators, and many stakeholders. It is expected this project will have several of these in common.
UCL are the key collaborator for THz comms and we aim to set-up a PhD studentship

Deliverables

1	**Start: 01/01/13**	**End: 30/06/13**	**Cost:**
Deliverable title: Begin to develop high-frequency metrology with new 220 GHz VNA Capability available in readiness for EMRP 'HF-CIRCUITS			
2	**Start: 01/01/13**	**End: 30/06/13**	**Cost:**
Deliverable title: **Establish Error Vector Magnitude measurement capability in optical domain to 10 GHz** Proof-of-principle experiment determined in readiness for EMRP 'MORSE'			
3	**Start: 01/10/13**	**End: 31/12/15**	**Cost:**
Deliverable title: Develop metrology to characterise the performance of free space terahertz comms devices and systems in frequency range 0.3-3 THz Collaboration with UCL and minimum of two published papers			
4	**Start: 01/01/14**	**End: 31/12/15**	**Cost:**
Deliverable title: Develop higher frequency non-linear standards for waveform metrology			

Project No.	EMT 13019	Price to NMO	£412k
Project Title	**Metrology for new electrical measurement quantities in high-frequency circuits (Co-funding for EMRP SIB62)**	Co-funding target	€403.4k (in place)
Lead Scientist	Nick Ridler	Start Date	July 2013
Scientist Team	Martin Salter, Chris Eio, David Humphreys Matthew Harper, Tian Loh	End Date	June 2016

Summary

The capability and functionality of test instrumentation enabling state-of-the-art high-frequency electrical circuit analysis has advanced dramatically during the past 5 to 10 years, but traceability to the SI has lagged behind these technical developments. This lack of traceability introduces a barrier to the use of this instrumentation in high value, high impact, fields – for example, medical, security, consumer electronics and environmental monitoring uses. This project cofunds an EMRP project that puts in place traceability and dissemination mechanisms for these measurement quantities such as mixed-mode *S*-parameters, *X*-parameters and *S*-parameters at millimetre- and submillimetre-wave frequencies

The Need

The technical requirements of cutting-edge high-frequency industrial electronics applications have driven test equipment manufacturers to develop new types of instrumentation. Lack of traceability has an impact on trading and the supply chain - for example, in medical, security, consumer electronics and environmental monitoring and the progress required by the International Technology Roadmap for Semiconductors (ITRS) and the roadmap compiled by the EURAMET Technical Committee on Electricity and Magnetism (TC-EM). Calibration and test laboratories conforming to the ISO/IEC 17025 international measurement accreditation standard require coherent traceability routes from NMIs in order to demonstrate to third party accreditation bodies the validity of the traceability of their own customer calibration services. These laboratories provide the measurement quality infrastructure for manufacturing, R+D and Academia in Europe and elsewhere.

The Solution

This project will develop the SI system to impact the emerging areas of technology that use RF, microwave, millimetre-wave and submillimetre-wave electromagnetic science and technology. Research and development will be undertaken to achieve traceability between existing SI units and the new and evolving quantities and units that are being used in these sectors and the linkage will be established between ISO/IEC 17025 accredited laboratories, test equipment manufacturers, end-user measurement laboratories (in industry and academia) to ensure effective knowledge transfer and maximum impact.

Project Description (including summary of technical work)

NPL has involvement in all 5 technical work packages (see below) of the EMRP Project as well as providing the lead on work package 3 and coordination of the whole project.

- Workpackage 1: traceability for reflection and transmission measurements in metallic waveguides to 1100 GHz and in coaxial lines to 110 GHz
- Workpackage 2: traceability for multi-port Vector Network Analyser (VNA) techniques and automatic (i.e. electronic) calibration techniques
- Workpackage 3: traceability for differential *S*-parameter measurements of planar circuits to test signal integrity
- Workpackage 4: traceability for nonlinear measurements and extreme load impedances
- Workpackage 5: improve vector measurement uncertainty evaluation techniques and verification processes and will develop international guides and standards
- Workpackage 6: ensure that the outputs from workpackages 1 to 5 achieve maximum impact on the stakeholder community
- Workpackage 7: overall management of the project

Impact and Benefits This project will address the major limitations affecting the validity of measurements made at high-frequencies (from RF to submillimetre-wave frequencies). The primary benefit will be greatly improved trade between customers and suppliers of products, both in Europe and the wider global community. The standards developed will impact areas such as <u>Medical diagnostics</u>, where traceable RF reflection measurements are required for scanners (for breast cancer detection, etc.); <u>Security and detection systems</u>, where reliable millimetre-wave measurements enable stand-off detection of fire-arms during, for example, airport security scans; <u>Consumer electronics</u> – e.g. desktop and laptop computers, mobile and smart 'phones, etc. - where state-of-the-art high-speed digital technology underpins performance.

The international perspective to this project will ensure global influence by development of the SI. Additionally, participation in international Working Groups (e.g. developing the IEEE P287 ‘coaxial connector’ standard; the IEEE P1785 ‘waveguide above 110 GHz’ standard; and, the IPC Printed Circuit Board TM 650 Test Methods) will be achieved, in Workpackage 5, through close cooperation between these international groups and the project partners. A third IEEE standard-related activity, in the area of defining nonlinear measurement quantities (which is soon to be started) will also be significantly influenced by the partners, through Workpackages 4 and 5. In fact, for all the standards and Guides described in this JRP, the project partners already play leading roles in these activities and this will ensure maximum leverage and impact of outputs from this JRP.

Support for Programme Challenge, Roadmaps, Government Strategies

This project supports the NMS Digital challenge by delivering measurement capability to “the industries that require high speed instrumentation” and the NMS Growth challenge by “stimulating and enabling innovation in products and services”.

Synergies with other projects / programmes

The project also aligns with broader European visions, as outlined in the Europe 2020 Strategy and echoed in the EURAMET 2020 Strategy – for example, relating to flagship European initiatives such as “A Digital Agenda for Europe”.

Risks

NPL technical risks involve the use of innovative science and the requirement to use leading edge network analysis, the design and fabrication of both suitable reference PCBs and non-linear verification devices, and sufficient accuracy of electromagnetic models. Across the whole project, the main risk is that the partners do not have the resources to deliver their parts of the projects or do not work together in a collaborative way. In addition the project relies on three REG organisations and two unfunded industrial partners. Many risks are mitigated by effective project management and coordination.

Knowledge Transfer and Exploitation

The outcomes from this JRP will provide European NMIs with traceability services for all the new and evolved quantities and units described in the above workpackages. Direct contributions to and interactions with international standards development (specifically, IEEE standards) will also be made by the partners in this project. In addition, the current EURAMET Guide that impacts this sector of the industry will be comprehensively revised, bringing it up-to-date with current end-user requirements. This revised version will be submitted to EURAMET with the recommendation that it is published as an update to the existing version of the EURAMET Guide. Finally, knowledge generated by the project will be disseminated regularly throughout the lifetime of the project (and beyond). The ANAMET technology forum for high-frequency electrical metrology (www.npl.co.uk/anamet), which has run successfully at national level in the UK since 1993, will be extended to operate at the European level to provide a forum for six-monthly public updates on the project deliverables. In addition, existing major international conferences (such as the European Microwave Conference) will be used as a vehicle to deliver scientific papers and specific workshops targeting the relevant sectors of the end-user community.

Co-funding and Collaborators

The partners involved are outlined in the table below:

Name	Organisation	Country
NPL	NPL Management Limited	United Kingdom
CMI	Cesky Metrologicky Institut Brno	Czech Republic
METAS	Federal Institute of Metrology	Switzerland
LNE	Laboratoire national de métrologie et d'essais	France
PTB	Physikalisch-Technische Bundesanstalt	Germany
SP	SP Sveriges Tekniska Forskningsinstitut AB	Sweden
VSL	VSL B.V.	Netherlands

Deliverables

1	Start: 1/07/13	End: 30/06/16	Cost: £412k

Deliverable title: Co-funding for EMRP SIB62 HF-Circuits Project

Evidence: Meets the technical, financial and impact delivery requirements of EMRP-MSU

Project No.	EMT 13020	Price to NMO	£600k
Project Title	**Real World Electromagnetic Metrology**	Co-funding target	
Project Lead	Matthew Harper	Start Date	01/01/2013
Project Team	Tian Loh, Phil Miller, Martin Alexander, Ben Loader, David Cheadle, Richard Dudley	End Date	31/12/2015

Summary A project to address the increasing demand for industry to make rapid, low cost, environment independent measurements but with an uncertainty and traceability close to that of an accredited facility. The cost of component testing and quality control within the manufacturing industry can reach unacceptable levels, particularly in high volume or multivalued testing where a choice has to be made between low-uncertainty rigorous testing or higher-uncertainty fast testing. This project focuses on developing measurement methods in two key application areas: small ultra wide band antennas and wireless sensor networks, using a strategy built on the use of measurement techniques in ad hoc environments The combination of ad-hoc measurement environments using novel materials and reference antennas for validation will lead to the ability to test wireless communication systems and EMC outside of purpose built chambers.

The Need Continuous improvement drives industry costs down and capability/complexity up. Also, changes to the RF spectrum landscape driven by ICT development and faster world bring new challenges. The issues addressed in this project and the related EMRP project are:

The Application	Measurement need
1: Release of RF spectrum (Ofcom) and EMC	a: EMC test standards (eg.EN60601-1-2) extended to 2.5 GHz will need to match new bands (LTE 2.6 GHz, 3.7 GHz). Poor uncertainties for GTEM cells above 1.6 GHz b: Signals and interference not CW or Added-Gaussian-White-noise c: Need for lower cost alternatives but with adequate performance.
2: Wireless communication and networks	a: Compact high data-rate ultra-wideband (UWB) antennas: Difficult/costly to measure. b: Multiple-In, Multiple-Out (MIMO) antennas present problems for Over-The-Air testing c: Directable antennas are slow to test (capacitance loaded and plasma) d: Reliable test methods for body-worn antennas
3: Testing/commissioning satellite antennas and systems	a: Increased complexity extending final testing time. Unacceptable cost risks b: Need to measure superposed RF modulated signals c: Accuracy must not be significantly degraded.
4: Wireless sensor networks/ machine-2-machine communication.	a: High cost/poor reproducibility of wireless-sensor-networks (WSN) measurements b: Growth area compared to voice. Needs cost-effective measurements. c: Low-cost test methods for RFID

The Solution The project activities reflect the measurement needs. The majority of work will be carried out with industry (I), academic (A) or NMI/EMRP (E) collaborators.
1a: Improve GTEM cell metrology, 1b: Interference/non-CW EMC Gather information from industry (e.g. ICTKTN and DTG) determine if measurement or specification issue (I*). 1c: Using (1a), determine trade-off for efficient measurement/accuracy, disseminate.
2a: Novel measurement techniques of small UWB antennas (A). Reduce complexity and cost, disseminate. 2b: MMO metrology JRP i011 2c: Use techniques from 2a, 2b and 3 to provide fast/efficient measurement process (A, E, I)
3a/b: Controlled reproducible environment for wireless sensor networks (A). Examine the effect of non-Gaussian interference (A). 4c: Develop robust, low-cost methods to test RFIDs/can effect of goods, simulated to reduce cost (I*).

Project Description
1 Improve GTEM cell metrology for performance under loads up to at least 5 GHz. Target uncertainty 3 dB. Collaborate with industry to provide metrology support interference and EMC testing. Analyse for value-engineered solutions and use of complementary metrology to improve efficiency.
2. Advanced antenna measurements: Develop and verify a sound methodology for Over-the-air (OTA) testing of MIMO and adaptive antenna Traceable RF power measurement for (OTA MIMO) systems. Use the techniques developed to improve the efficiency of UWB, Directable antennas and body-worn antennas. (I, A, E)
3: Develop a customizable electromagnetic environment, using for example metamaterials, frequency selective surfaces, and related methodologies, that can be shown to simulate real-world electromagnetic behaviour for a given application. Test applications such as Wireless Sensor Networks and Smart M2M under stressed conditions. Investigate value engineering for low-cost systems and opportunities as a national infrastructure facility.(A)

Impact and Benefits 1: Strategic: NPL will gain facilities and expertise to lead these technologies at an international level and adapt to technology developments. Maintain NPL's position as a focal point for these technologies. Support standardisation.
2: Tactical: Outputs from the research will improve, through speed or accuracy, dissemination through NPL measurement services. This should reduce time, and hence cost, to the users.
3: Wider use: RF capital facilities are expensive. Concentrating on a metrology-based value engineering approach will allow SMEs and universities to build low-cost facilities. This will support the EPSRC strategy.
4: Commercial: NPL is a world leading NMI for microwave antenna measurement metrology. This is a strong dissemination route and the 3rd party reduces the overall cost to NMO.
5: Knowledge: Much of the impact delivery is through knowledge transfer by publications and contribution to international standardisation. Expertise and collaboration supports UK industry and academia.

Support for Programme Challenge, Roadmaps, Government Strategies 1: The project aligns with the NMS 'Digital Economy' strategy and the 2020 Digital Agenda for Europe, identified as a prerequisite for Growth; COST 2100.
2: High-efficiency antenna systems support Energy agendas and reduce Operational expenditure. 1 dB sensitivity loss equates to 14% coverage loss for wireless communication (ICTKTN).
3: International standardisation effort through IEC and ETSI.

Synergies with other projects / programmes The project supports concurrent projects: EMRP IND 16 and EMT 13018 "Faster World". It builds on the NPL knowledge base (2009-2012 projects: 5.1 & 5.4) and Measurement services facilities used in these projects will benefit from the project outputs. Note the EMRP IND 51 (MORSE) project was successful and a significant part of the planned work in this project has been moved into a separate co-funding project to support that work which starts in July 2013.

Risks 1: Change of priorities by collaborators. Mitigation (several collaborations where possible). May affect deliverables.
2. Technical risks: (1) GTEM cell at uncertainty limit, (2) Available statistics through customisable environment do not mimic real-world scenarios.

Knowledge Transfer and Exploitation
1: The main technology transfer is through International peer reviewed publication, e.g. IEEE Trans. or Letts. papers and IEEE Explore searchable conferences (>11 papers expected overall with related MORSE project).
2: Sensors and Instrumentation KTN, ICTKTN (RF Spectrum and other groups), ICOST 1004 will act as conduits both to disseminate and to advise.
3: Links with standards bodies IEC (EMC) and ETSI (RF Communications antennas, MIMO).
4: Direct pursuit of IPR if appropriate. New facilities or extensions to existing facilities will be advertised and good-practice guides prepared for value-engineered approaches if appropriate.
5: GTEM cell results will be disseminated through the GTEM user group in addition to (1) & (4).

Co-funding and Collaborators
1: EMRP IND 51 (MORSE) has industry collaborators, and 9 stakeholders.
2: University of Liverpool and University of Surrey provide expertise in UWB small antenna design/synthesis, antenna measurement techniques and as well as fabrication of the prototype UWB small antennas
3: University of Warwick provides expertise in metamaterials, frequency selective structures, and numerical simulation techniques as well as technical advice on fabrication of the ad-hoc EM environments and antenna measurements:
4: University of Surrey provides technical advice and in supervise in areas of novel designs and implementations

Deliverables

1	**Start: 01/01/2013**	**End: 30/06/2013**	**Cost:**
Deliverable title: Investigate potential for metrology for MIMO			
2	**Start: 01/01/2013**	**End: 31/12/2015**	**Cost:**
Deliverable title: "Develop customizable electromagnetic environment to simulate real world EM bevaiour and test WSN applications under stressed conditions"			
3	**Start: 01/01/2014**	**End: 31/12/2015**	**Cost:**
Deliverable title: "Improve GTEM cell metrology" *evidence:* (a) publication quality test results (b) Improvements to NPL measurement capability. (c) Dissemination to industry.			
5	**Start: 01/01/2015**	**End: 31/12/2016**	**Cost:**
Deliverable title: OTA characterisation of MIMO and develop full MIMO measurement system.			

Project No.	EMT 13021	**Price to NMO**	£402k
Project Title	**Cofunding for EMRP IND 51 MORSE (Metrology for optical and RF communication systems)**	**Co-funding target**	€397.2k (in place)
Lead Scientist	David Humphreys	**Stage Start Date**	1/7/2013
Scientist Team	Tian Loh, Irshaad Fatadin, Philip Miller, Matthew Harper, David Cheadle, Peter Harris (maths)	**Stage End Date**	30/6/2016

Summary High quality satellite, fibre and mobile communications are an essential part of modern life and vital to our wealth-creating industries. The EU *"2020 Digital Agenda for Europe"* acknowledges this and sets ambitious targets that will have an impact on all areas of the communication network and offers significant opportunities for European industry. However, the potential technologies are complex and reliable measurement is required to develop and test innovative solutions so that these technologies can be integrated within the shortest possible timescales and at the lowest cost.

This project delivers the metrology in the three key technologies of adaptive wireless systems, communication satellites and optical networks to stimulate innovation and enable their rapid uptake and integration into the infrastructure.

The Need Communications is a high-value technology infrastructure that grows, driven by demand, at 40%pa. Each successive generation of products are at the state-of-the-art. The alternatives to new technology are to install more capacity (optical fibre), which is hugely expensive; curb demand through price; or to run out of capacity. There is also a need to improve power efficiency, to achieve European sustainability targets and maintain the climate change agenda. The challenge for manufacturers is to develop and test increasingly high-bandwidth products at a reasonable cost. There is a need for new and innovative metrology to support the development of the next generation of components and test-equipment by many manufacturers.

The Solution The requirement is to ensure that individual elements of the system perform as expected and can therefore be integrated. The key to this is the provision of traceable measurements as a platform to enable the individual providers to collaborate. This project provides the solution through the simultaneous development of traceability in three key areas (see project description) to ensure that the outputs are coherent in terms of their ability to deliver integration**.**

Project Description (including summary of technical work) NPL provides technical expertise to all the work packages, leads work package 3, and is the coordinator for the whole project as described below:

- Workpackage 1: Key technology 1. Adaptive wireless systems (1) Measurement of radiated RF power and (2) Over-The-Air testing for 4G (and above) systems such as LTE and LTE-advanced where the transmitters and handsets have several antennas; and (3) Traceable measurement methods for low-cost reconfigurable
- Workpackage 2: Key technology 2. Communication satellites. (1) Verified algorithms that balance measurement, modelling and interpolation to reduce test-time (2) Develop a nearly non-invasive electric field sensor to test small antennas at high frequencies (> 60 GHz). (3) Improve the accuracy of the large testing facilities. The sensor developed in (2) will be used in this work. (4) The effect of environmental factors on measurement uncertainties - testing antennas under temperature and stress.
- Workpackage 3: Key technology 3. Core optical network capacity 1) develop the supporting metrology for the transmitters and receivers, new terminal and test equipment etc to achieve up to 1Tbit/s in a single channel.
- Workpackage 4: Engage with the industry communities to maximise the impact
- Workpackage 5: Project management and coordination

Impact and Benefits The impact is illustrated by two examples. Over-The-Air testing of MIMO and other advanced antenna systems presents significant metrology challenges. Measurement of MIMO power is important because a 1 dB loss of sensitivity of the user equipment (UE) corresponds to a 14% reduction in the effective cell size, which has implications for quality of service, planning and operational costs.
Large satellite communication systems have typical turnaround times of 24 months with costs in the range 400-650 M€. Test and validation times are critical and occur at a high-cost stage in the programme cycle. The state-of-the-art satellites can simultaneously create multiple transmission beams that cover different areas on the earth's surface and this increased complexity extends the test duration. Reliable and robust methods to cut the test-time by a factor of two or more are needed to maintain the tight delivery-schedules

Support for Programme Challenge, Roadmaps, Government Strategies This project directly supports and focusses all its impact on the NMS strategy Digital Challenge to: “Develop measurement methods to underpin the specification and reliability of the technology for next generation communication systems”

Also the digital agenda for Europe “*Digital Infrastructures – both physical and service based –are key enablers for the smart growth that Europe must achieve in the coming ten years in order to ensure its ability to compete internationally and generate wealth for its citizens”*

Synergies with other projects / programmes The project aligns with broader European visions, as outlined in the Europe 2020 Strategy and echoed in the EURAMET 2020 Strategy – for example, relating to flagship European initiatives such as “A Digital Agenda for Europe”.

Risks NPL technical risks involve the use of innovative science and the requirement to use leading edge highly complex MIMO systems, the difficulty in improving planar scanning accuracy and achieving sufficient accuracy of transform algorithms and uncertainty propagation models. Across the whole project, the main risk is that the partners do not have the resources to deliver their parts of the projects or do not work together in a collaborative way. In addition the project relies on two REG organisations and four unfunded industrial partners. Many risks are mitigated by effective project management and coordination.

Knowledge Transfer and Exploitation Knowledge transfer will be guided by an advisory board of stakeholders and collaborators that will advise on the best format and KT channels including Journal publications, Conference presentations, a project website a project newsletter.
The consortiums established links to the following standardisation activities will be used to progress standards.

- International Electrotechnical Commission, IEC, Technical Committee TC85, TC86, WG4
- Deutsche Kommission Elektrotechnik, DKE, Komitee 964
- The 3rd Generation Partnership Project (3GPP), RAN4 Group.
- International Telecommunications Union

Best practice guides and other protocols and procedures for industry use will include

- Guidelines for the evaluation of uncertainties when measuring LTE signal with diode based sensors (WP1)
- Report of the sensitivity of LTE R_0 measurements with respect to multipath propagation (WP1).
- Guidelines for the alignment of a scanner inside a compact range for the measurement of Quiet zone field (WP2)
- Guidelines for the use of sub-Nyquist sampling and combined modelling in antenna measurement (WP2)
- Guidelines for the full-waveform characterization of photodiodes using an electro-optic test bench (WP3)

Web courses
Taking advantage of new media, web courses have the potential to reach a very broad audience, which, in this form, is not accessible by local meetings or even international conferences. The JRP consortium will create one web course per scientific work package, in which new measurement or calibration techniques will be discussed. The web courses will be uploaded to the JRP web page.

Co-funding and Collaborators
The collaborators are outlined in the table below:

Short Name	Organisation	Country
NPL	NPL Management Limited	United Kingdom
CMI	Cesky Metrologicky Institut Brno	Czech Republic
METAS	Federal Institute of Metrology	Switzerland
LNE	Laboratoire national de métrologie et d'essais	France
PTB	Physikalisch-Technische Bundesanstalt	Germany

Deliverables

1	Start: 1/07/2013	End: 30/06/2016	Cost:

Deliverable title: Cofunding for EMRP IND51 ‘MORSE’ Project
Evidence: Meets the technical, financial and impact delivery requirements of EMRP-MSU

Project No.	EMT 13022	**Price to NMO**	£940k
Project Title	**Electromagnetic Science for Space and Remote Sensing**	**Co-funding target**	
Project Lead	Richard Dudley	**Start Date**	01/01/2013
Project Team	Tian Loh, Matthew Harper, Stephen Protheroe, James Miall, John Howes,Martin Alexander,	**End Date**	30/06/2016

Summary:

The primarily objective of the project is to provide traceable microwave metrology for space qualified assemblies to 220 GHz. Measurements include the calibration of radiometers, receivers, antennas and quasi-optic sub-systems. Space antenna characterisation and development is already a major NPL strength; however measurement capability is falling behind demand from the space industry. The UK has a significant manufacturing base producing space qualified microwave equipment, but yet lacking traceable measurement above 50 GHz. NPL already provides a highly regarded service to the space industry; a project to combine existing capability with new science will support future European space missions and give confidence in the critical decisions made from the data.

The Need:

ESA are initiating the procurement of three earth observation platforms to operate with channels to least 220 GHz and experimental channel as high as 800 GHz. The UK is a world leader in the manufacture of microwave satellite componentry and complete payloads and has a high probability of winning the procurement. The procurement processes require manufacturers to perform the calibration of all equipment; however the lack of available microwave space tailored standards drives the development of in-house techniques. Pre-launch calibration error has already been identified in a number of earth observation platforms utilising microwave channels to collect data about climate change and weather prediction. To strengthen the UK space offering and secure further growth, the role of a strong supporting metrology capability cannot be overlooked. ESA and international space agencies are recognising that current pre- and post-launch calibration of microwave payloads are weakness and NPL has an opportunity to lead through higher frequency traceable measurements and space specific services.

The Solution:

The project will target space specific requirements at higher frequencies supported by the development of measurement of key microwave parameters. In antenna measurement this means extending operating frequencies from 110 GHz to 220 GHz in the spherical antenna ranges and developing new techniques for smart materials and antenna structures where beam scanning is achieved electrically rather than mechanically. NPL has developed expertise and IP in smart antennas which shall be utilized and exploited further. Discrete devices and quasi-optic structures require the project to address radiometer hot/cold targets, channel bandwidths/linearity; all underpinned by advances in traceable power, noise and attenuation standards at elevated frequencies.

Project Description:

1) A primary noise standard at frequencies >110 GHz using a total power cryogenic primary standard, requiring a WG29 radiometer new calculable primary noise standard
2) Extend power metrology from 110 GHz to 220 GHz, in partnership with University of Birmingham.
3) Measurement strategies developed for radiometer hot/cold target calibration, receiver channel bandwidth and linearity calibration >110 GHz.
4) Extension of antenna chamber operation to 220 GHz by assessment of RAM effectiveness and practical delivery of signals to feed horns. Antenna gain, efficiency and side lobe measurement to 170 GHz, then progressed 220 GHz.
5) Development of free-space calorimeters to provide broadband power traceability at 10 to 100 μW levels for pulsed and CW > 200 GHz using a dual load method relating DC and incident THz to the heating effect, through a low-loss window, in a low heat capacity absorption cell.

Impact and Benefits: European capability for measurement and calibration is limited; for future satellite business growth in the UK, effective metrology support will enable product verification and competitiveness in the UK and Europe. The UK is poised to bid for 3 microwave payloads valued at > £30 million; a UK metrology capability can help to secure the business. Greater accuracy and traceability of earth observation data will lead to greater accuracy in meteorology, climate prediction and the use of the earth's resources. Involvement in the design and testing of smart and flexible antennas will lead to lighter and longer lifetime payloads for future missions. At present suppliers of equipment for payload are effectively attempting to construct their own primary standards with varying degrees of success. Establishing the accuracy and inter-comparability of these systems will give greater confidence in resulting measurements and enable uncertainties to be lowered.

Support for Programme Challenge, Roadmaps, Government Strategies: This project supports the NMS strategy aim of 1) "Establish increased confidence in Earth Observation data on climate change by developing instrumentation and techniques for data validation and by leading the introduction internationally of long-term reference methods" and 2 "**Develop** measurement methods to underpin the specification and reliability of the technology for next generation communication systems". Satellite and space metrology supports UK Growth and Environmental government strategies and matches the EPSRC priority areas in higher frequency measurement.

Synergies with other projects / programmes: The faster world and real world EM projects, dielectric materials and terahertz projects. With high success in recent ESA projects, further bids will be supported by this work. In the future NPL should be positioned as the ESA laboratory of choice for microwave testing. NPL is the world leading NMI for free field metrology, and to continue to generate 3rd party income investment is required.

Risks: Operating at elevated frequency presents new challenges which can both drain resources and have high costs. Partnering the frequency extension stage of the project with EMRP both increases the resources and the ability to solve any issues.

Knowledge Transfer and Exploitation:

A successful outcome of developing the NPL metrology and science in this area will be to secure future microwave instrument and component fabrication within the UK. NPL will lead the international NMI offering and creating a future traceability platform for all airborne instruments. Publications at international conferences and in the scientific literature will be obligatory. Membership of the CEOS microwave group has already been advanced, and NPL will use this as a mechanism to influence the international space agencies.

Co-funding and Collaborators

Collaborators with commitment include the Universities of Surrey, Glasgow and Birmingham

Deliverables

1	**Start: 01/01/2013**	**End: 31/12/2014**	**Cost:**
Deliverable title: Develop WG 29 primary radiometry-based noise standard 110 GHz-170 GHz			
2	**Start: 01/01/2013**	**End: 31/12/2014**	**Cost:**
Deliverable title: Develop antenna measurements to 220 GHz including gain, efficiency and side lobe capabilities Paper published and capability for higher frequency antenna metrology available.			
3	**Start: 01/07/2013**	**End: 30/06/2016**	**Cost:**
Deliverable title: Extend power metrology from 110 GHz to 220 GHz Paper published and standards for millimetric power available.			
4	**Start: 01/01/2015**	**End: 31/12/2016**	**Cost:**
Deliverable title: Development of free-space calorimeters > 220 GHz			
5	**Start: 01/01/2014**	**End: 31/12/2015**	**Cost:**
Deliverable title: Space specific measurement systems for hot/cold target calibration, receiver channel bandwidth and linearity calibration			

Project No.	EMT 13022	Price to NMO	£250k
Project Title	**Metrology for Smart Antennas**	Co-funding target	
Lead Scientist	Tian Hong LOH	Stage Start Date	01/01/2013
Scientist Team	Richard Dudley, Phil Miller, Mira Naftaly, Martin Salter, David Cheadle	Stage End Date	31/12/2015

Summary The aim of the project is to investigate and deliver measurement methodologies for the characterisation of novel smart antennas. Due to the ability of suppressing interference, combating against fading, improving data capacity and radio coverage and providing new services, smart antennas have become the key technology for realising next-generation wireless communications, satellites, radars. However, their innovative design and cost-effective measurement capability is falling behind demand from the telecommunication industry. This project focuses on developing methodologies in a number of novel smart antennas such as small electronically beam-steerable parasitic array radiator (ESPAR), ultra-wideband (UWB) antenna array, Reconfigurable reflectarray, and plasma antenna, etc. Novel techniques of reducing antenna size will be investigated by using novel materials such as meta-materials, liquid crystals, and wire mesh substrates. For optimum control of smart antenna robust adaptive beamforming algorithms will be investigated.

The Need Smart Antennas can adaptively form narrow directional beams towards the intended users, while forming a null towards the interferences sources and they are the key technology for wireless communication, satellites and radars. They can improve the capacity of wireless communication networks significantly, increase the spectrum efficiency and reduce the transmit power. Many technologies of smart antennas have been proposed, including digital beamforming array antennas, passive and active phased array antennas, analogue beamforming arrays, switched-beam array antennas, multiple inputs and multiple outputs systems, etc. However, these smart antennas are rather complicated, bulky, heavy and expensive. On the other hand, accurate measurements of smart antennas are at presnt very time consuming and involve complicated procedures, leading to higher cost. These drawbacks restricted the development of smart antennas. For wide applications, future wireless systems will need low-cost small smart antennas and cost-effective measurement methodologies. This work proposes to radically improve the metrology available to meet these future needs.

The Solution This project will focus on developing metrology that can cope with the needs brought about by the convergence of innovations in multiple disciplines such as antennas, RF/microwave circuits, novel materials, digital signal processing (DSP) algorithms, and Field-Programmable-Gate-Array (FPGA). Through this project, NPL will investigate these novel designs and measurement metrology of small reconfigurable antennas that will enable the development of efficient and accurate metrology methods, new capabilities and skills for smart antennas. This will include the design of novel test anteannas with the features and performance required to test the metrology.

Project Description (including summary of technical work) Smart Antennas can adaptively form narrow directional beams towards the intended users, while forming a null towards the interferences sources. Thus the use of smart antenna can significantly increase the data rate and enable the next-generation satellite communications, wireless local area network (WLAN) and wireless personal area network (WPAN) ecosystem. Combining the advantages of reflector antenna, microstrip patch array, small antenna, smart antenna, novel material and adaptive beamforming algorithm technologies, the project will investigate the novel design of smart antennas which can achieve electronically beam steering and nulling and the novel cost-effective measurement methodologies for characterizing smart antennas prior to and after incorporation of the transceiver that includes forward-error correction (FEC) coding and modulation. Important parameters such as radiation pattern, gain, efficiency, signal-to-interference ratio (SNR), etc. will be investigated. The new science will lie in exploring the novel low-cost low-power high-gain smart antenna solutions by considering various array/imaging configurations, antenna elements, low-cost phase tuning mechanisms, novel materials, etc. and showing how their measurements can be done cost-effectively. Also, this project will demonstrate and measure the performance improvement gained by the incorporation of novel low-cost smart antennas to wireless sensor networks and build upon existing systems.

Impact and Benefits The main driver for the project is to support the rapid growth of the wireless communications market, with increasing requirements for functionality, energy efficiency and robustness of communications. This project aims to deliver innovative measurement technologies that can be exploited in the UK supply chain. This study allows NPL to gain facilities and build expertise in novel smart antennas characterization for enabling new cutting-edge wireless applications and allows NPL to lead these technologies at an international level and adapt to technology developments. The findings in this emerging technology will be useful for a variety of applications such as mobile communication base stations, mobile handsets, wireless local area networks, satellites, radars and software-defined radio.

Support for Programme Challenge, Roadmaps, Government Strategies
This project responds to the Science ministers wish that NPL;*"Makes better use of the existing facilities by strengthening the Laboratory's links with its academic partners, through new and existing collaborations with academia and industry; and Encourages greater interaction with business, driven by closer integration of existing innovation infrastructure and commercial activity"*.
It also delivers to the current NMS Strategy Digital Challenge aim to "Develop measurement methods to underpin the specification and reliability of the technology for next generation communication systems".

Synergies with other projects / programmes
The project supports concurrent co-funded projects – EURAMET-i011 (MORSE) project and the other EMT project "Real world electromagnetic metrology". This project will bring together multi-disciplinary technical expertise, which involves input from the Electromagnetic Technologies group and the Electromagnetics group, and lead to important advancement in this fast moving field. It builds on NPL knowledge base (2006-2009 projects: W3 & W4; 2009-2012 projects: 5.1 & 5.4). Also it helps to enhance the work carried out on the RF and Microwave Capability and Infrastructure project in the Electrical Theme and the development of existing advanced RF, and Microwave facilities.

Risks
Links to external activities and capabilities, as control of these is not governed exclusively by NPL. For example: collaborations for university groups, NMI partners in EMRP projects.

1. Change of priorities by collaborators. Mitigation: several collaborations where possible.
2. Technical risks: insufficient plasma element density for driving the configurability of smart plasma antennas. Mitigation: active-integrated-antenna technique will be investigated.

Knowledge Transfer and Exploitation
The capabilities and skills developed on design and measurement methodologies will constitute IP, and form part of a wider NPL-based consultancy and measurement service. It is envisaged that NPL will take it forward via NMO and/or other industrial venture funding routes and apply the metrological outcomes to various emerging wireless technologies. Publications at an international conference and in the scientific literature will be the aim unless it is decided that pursuit of IPR makes that unwise. NPL has developed expertise and IPs in smart antennas technologies which shall be utilised and exploited further. The project outcomes and findings will be disseminated through the Cambridge Wireless testing SIG, Sensors and Instrumentation KTN, the WiSIG and other KTNs.

Co-funding and Collaborators
NPL is currently engaging with key players in the space industry to build relationships around the emerging technologies associated with smart antennas. This will result in NPL/Industry/academic partnerships involving the following partners:
1: University of Kent, University of Liverpool, and University of Surrey provide expertise in antenna design/synthesis, antenna measurement techniques as well as fabrication of prototype antennas.
2: University of Warwick, Queen's University of Belfast and Queen Mary University of London provide expertise in novel materials such as metamaterials, liquid crystals, frequency selective structures, and numerical simulation techniques.

Deliverables

1	**Start: 01/01/2013**	**End: 31/12/2015**	**Cost:**
Deliverable title: Collaboration with Academic partners to produce a reference smart antenna. **Evidence**: Report on characterised smart antenna, the metrology method and the UP Protected			
2	**Start: 1/01/2014**	**End: 31/12/2014**	**Cost:**
Deliverable title: Plasma Antenna profile measurements and assessment of phase tuning capability. **Evidence**: (a) Design, construction and initial characterisation of a test plasma antenna; (b) Novel designs of high gain smart test plasma antennas; (c) Measurement service for low-cost smart plasma antennas.			
3	**Start: 01/01/2014**	**End: 31/12/2015**	**Cost:**
Deliverable title: Innovative measurement methodologies for adaptive and reconfigurable smart antenna **Evidence**: (a) Investigate adaptive beamforming algorithms; (b) Investigate important antenna parameters such as signal-to-interference ratio (SIR), radiation pattern, gain, efficiency, etc.; (c) Incorporate smart antennas to wireless sensor networks.			

Project No.	EMT 13024	Price to NMO	£530k
Project Title	**Metrology for Smart Grids**	Co-funding target	£300k
Project Lead	Paul Wright	Stage Start Date	01/09/2013
Project Team	Paul Wright, Paul Clarkson, Alistair Forbes, Adrian Wheaton	Stage End Date	31/06/2015

Summary: The objective of this project develop approaches to best address the measurement of electrical energy generated, distributed and used on high-voltage grids including the UK national grid. The project proposes a toolbox of four new metrological capabilities that will address the key issues of revenue settlement, plant efficiency, power quality compliance, grid based measurements and sensors to ensure stable power flow. The project will build on capabilities being developed in existing EMRP projects and pave the way for future Energy metrology as foreseen on the Euramet Roadmap. Successful implementation and operation of SmartGrids depends directly on the measurements needed to control the power flow & quality and to settle the revenue exchange. Whilst technologists propose and trial an ever increasing array of SmartGrid systems, their success uptake will depend on proving their robustness, and capability in the field through industry trusted measurements.

The Need: SmartGrids are highly complex systems with multiple and diverse inputs and outputs which have the potential for rapid and severe instability/ blackout, resulting in serious social and economic consequences. In order to control such Smart systems, reliable and actionable measurements are required to ensure that carbon intensity is minimized whilst never compromising power quality and system stability. The toolbox of measurements proposed here will provide some of the more urgent metrology infrastructure, to underpin emerging technological developments. Smart grids/meters are highly consistent with Governments Sustainability policy which is being implemented though technology based research programs. Funding bodies such as OfGEM consider that grants should be spent directly on Smart technology trials which leave a gap in the provision of the required new metrology infrastructure. This project will develop the NMS world leading capabilities beyond the State of the Art to provide a metrology infrastructure that enables stable, high quality future energy networks.

The Solution: The project will deliver 3 new capabilities utilizing previously NMS funded digitizer hardware and algorithms to implement grid based measurements to determine i) three phase (3Φ) active and reactive power at accuracies suitable for revenue settlement. ii) On-site power and power quality parameters up to 33kV, 10kA. iii) in-situ compliance testing of power quality compliance installations to support emerging regulation. The project will apply these capabilities in support of SmartGrids implementations, and in particular in association with the roll out of SmartMeters in the UK, a new method (WP 4) to consolidate SmartMeter data in order to estimate power flow/system state is proposed.

Project Description: A new ***3Φ active and reactive power and energy capability*** would be developed in ***WP1***. The system would utilize the recently completed NPL digitizer as a 3Φ standard used to calibrate industrial instrumentation by substitution, the majority of the WP concentrating on the generation of 3Φ power and the software for control and measurement. The NPL digitizer was designed for on-site measurements and ***WP2*** would implement an ***on-site measurement capability***, this would include the commissioning of a 3Φ high voltage (33 kV) divider such that the efficiency and power quality of grid connected wind turbines and other renewables could be measured. Whereas WP2 would provide on-site measurements aimed at manufacturers of renewables, ***WP3*** proposes ***in-situ measurements of compliance testing facilities*** in support of international supply quality regulations. The NMS has funded a capability for NPL based compliance testing in previous programs, however new international standards calling for the equipment to be assessed in-situ, are likely to make the existing NMS facilities obsolete in the coming few years. WP3 with use the NPL digitizer as a remote calibration standard that will be sent to industrial premises; WP3 will develop a methodology using a "*Smart Impedance*" that can be used to modulate power using complex functions to exercise the dynamic range of the equipment under test. ***WP4*** is a research project that seeks to utilize the potential of the ***SmartMeter data for network state estimation***. SmartGrid designers will need to include a considerable amount of power flow monitoring in their future networks in order to monitor and control the stability of these low inertia networks. This instrumentation would require high voltage transformers and will be expensive to install and maintain. WP4 will determine whether the vast amounts of low accuracy Smart Meter data can be reliably used as an alternative. NPLs expertise in uncertainty and sensitivity analysis will be applied to investigate how this data can be aggregated to provide a similar or greater level of understanding of the grid state, allowing greater grid control and efficiency at a vastly reduced cost. Network measurements using the capabilities developed in WP1 & 2 will be required to verify this consolidation process and is hoped that a new methodology can be developed applicable to any network with SmartMeter coverage.

Impact and Benefits: Electricity supply is essential to society and the impact of an unreliable/poor quality culminating in supply interruption, which as has been witnessed recently in Japan and India, is catastrophic to the economy and quality of life. As the UK supply system is on the brink of radical redesign, the need for reliable measurements to support these innovative systems, monitor their stability and determine changes in quality of supply has never been greater.

The project will make several step changes to NMS capabilities which will directly support Smart Infrastructure innovation, ensure fair trade, enable supply system monitoring/control and implement emerging regulation. The final workpackage will apply these capabilities in a novel scheme that could be used to radically reduce the amount of expensive fixed installation energy flow monitoring systems that will need to be fitted to future networks, resulting in significant saving to electricity consumers.

Support for Programme Challenge, Roadmaps, Government Strategies: The project aligns with the NMS strategy vision This NMS strategy recognizes that "Smart grids and smart metering will play a role in saving energy and controlling energy demand" as outlined in the NMS energy challenge. UK Government is currently investing into the vision of a low carbon economy, driven at achieving the UK legal commitment set out in the 2008 Climate Change Act. Examples of funding include Low Carbon Network Fund [OfGem] >£500M for SmartGrids; DECCs Low Carbon Innovation Fund [£160M] and the Green Deal. This new infrastructure requires but does not fund new metrology solutions to enable performance assessment and ensure stability and quality. All work packages in the project explicitly appear in the Euramet Roadmap and supporting text for "Power and Energy in an era of emerging Smart Grids". The document Metrology 2020 further supports this vision….. The Proposed 2013 SmartMeter Rollout will cost consumers £14bn - one of the biggest criticisms of the proposal is the lack of extra applications and utilization of the data beyond those benefiting supply companies, this project will seek to utilize this infrastructure to ensure system stability at reduced cost whilst maintaining measurement rigor, thus ultimately benefiting consumers.

Synergies with other projects / programmes: The project will utilize hardware, software and mathematical techniques currently being developed in EMRPs "Metrology for Smart Grids" and "HVDC". It is aligned with Euramet Roadmap and the themes are likely to be further developed in the 2013 EMRP Energy Call.

Risks: WP4 relies on the UK SmartMeter roll-out which is subject to political delay. However, the methodology could be developed using SmartMeters in other countries pending a future UK system. HV dividers needed in WP2 would be subject to supply from a third party, we would need to mitigate the risk by seeking an alternative supplier.

Knowledge Transfer and Exploitation: Project exploitation would be though three new measurement services from WP1 to 3 respectively, aimed at electricity suppliers, renewable manufacturers and testing laboratories, and a consultancy service from WP4 aimed at network planners.

Co-funding and Collaborators: WP1 would benefit from some collaboration with EDF who have an interest in 3Φ measurements. WP2 would attract in-kind support from a Distribution Network Operator (DNO) or manufacturer of renewables to develop the capability. WP3 would be highly supported by UKAS and the EMC Testing Labs Association.

Deliverables			
1	**Start: 01/09/13**	**End: 30/06/15**	**Cost:**
Deliverable title: Develop Three Phase Active and Reactive Power and Energy Capability using NPL digitiser			
2	**Start: 01/09/13**	**End: 30/06/15**	**Cost:**
Deliverable title: Develop On-Site power metrology capability to measure efficiency and power quality of renewables			
3	**Start: 01/01/14**	**End: 31/07/16**	**Cost:**
Deliverable title: In-situ measurements of compliance testing facilities			
4	**Start: 01/01/14**	**End: 31/07/16**	**Cost:**
Deliverable title: Smart Grid Power Flow Estimation Using SmartMeter Data.			

Project No.	EMT 13025	**Price to NMO**	£310k
Project Title	**Metrology for Electromagnetic Health, Safety and Medical Applications**	**Co-funding target**	
Project Lead	Ben Loader	**Start Date**	01/01/2013
Project Team	Ben Loader, Mira Naftaly, Richard Dudley	**End Date**	31/12/2014

Summary: This project will ensure that electromagnetic field exposures (EMFs) exposures can be assessed accurately and rapidly in *industrial and medical environments,* for THz systems and in therapeutic applications of EMF. The work will allow implementation of 2004/40/EC, and facilitate medical applications of EMFs by providing electromagnetic dosimetry in-vitro and in-vivo dosimetry at THz frequencies. The project will also investigate new techniques for cell growth control using non-thermal microwave and terahertz energy as a solution for disease control.

The Need

1. Statistical sampling methodologies need to be developed to speed up on-site assessment for industrial and medical environments, for example MRI suites, in order to minimize the costs of implementation of EU directive EC95/40/EC (amended 2008). Many real environments have sources with non-sinusoidal waveforms and the sensitivity of field probes for these signals needs to be assessed. Stand-on current mats are a widely used tool for assessing ankle currents in the frequency range 100 kHz to 110 MHz, but at present there is no traceable calibration for these devices.
2. Terahertz Biology. THz effects on cells, including gene regulation and growth stimulation/suppression is an emerging area of bio-medical science which promises novel therapeutic modalities. Investigating and developing these applications requires traceable measurements for dosimetry, high-resolution temperature, and THz beam propagation and interaction with cells in vivo. 100 GHz to 3 THz radiation has been found to affect cell signalling and have both genotoxic and therapeutic. Work is needed to explore the effect in conjunction with accurate dosimetry for in-vivo and in-vitro research.

The Solution:

This project will address gaps in current metrology of electromagnetic fields (100kHz to 18 GHz), and will extend the upper frequency range to cover 18 GHz to 3 THz to facilitate health research and safety assessment for this region of the spectrum. In addition, metrology will be established to support imaging and therapies using terahertz. An initial investigating into the effects of low-power mm-waves on cancer cells in vitro will be extended to include THz suppression, stimulation, and gene regulation of a variety of cells in vitro, leading to trials in vivo. The frequencies and dosimetry for therapeutic effects will be determined. A delivery platform for the measured exposure and monitoring of cells in vitro will be developed. The project will be carried out in close collaboration with the Department of Cancer, Imperial College/Cancer Research UK.

Project Description:

The project will develop the following capabilities.

1. Calibration of E- and H-field meters to non-sinusoidal waveforms, based on existing field standards driven with function generator (up to 10 MHZ).
2. Characterization of the filter response of band-selective field meters through swept frequency calibration (100 kHz to 18 GHz) achieved using the GTEM1750 cell and double-ridged horn antenna.
3. Calibration system and method for stand-on induced current mats for (100 kHz to 110 MHz) and comparison with current clamp standards. A suitable system for injection known currents will be devised.
4. Statistical and combined measurement and analytic models will be developed for on-site exposure assessment in industrial and medical environments.
5. Investigate non-thermal interactions of THz radiation (0.1-2 THz) with living cells, normal and cancerous. Both therapeutic and genotoxic effects will be studied, including triggered cell death targeting cancer cells, growth stimulation of normal cells to aid healing, and gene regulation. Frequency regimes and dosimetry will be identified.
6. Metrology for field measurement and *in-vito* and *in-vivo* exposure will be developed for 100 GHz to 3 THz.

Impact and Benefits: Economy: minimizing the costs of implementing the EU directive, and facilitating development in medical applications of EMF. Quality of life: ensuring worker safety and enabling improvements in medical imaging and cancer treatments. Innovation: New methods for material characterization and SAR assessment. These aims support the NMS Strategy need to provide "Accurate measurement essential for assuring consumer protection, security, law enforcement, environmental and safety legislation and the quality of healthcare".
Innovation is supported through the advancement of medical applications of EMF and facilitating research into effects of THz radiation on biological systems, both for safety and treatments.

Support for Programme Challenge, Roadmaps, and Government Strategies: IMERA Roadmaps: EM Measurements, traceable THz for Health care, Safe working and public environments with respect to EMF exposure. Metrology for Healthcare devices: Reliable diagnostics and therapeutics. Information and comms tech: Field mapping metrology. DIUS: Nano Grand Challenges- Healthcare. TSB: Health care –Medical Devices and Instrumentation.			
Synergies with other projects / programmes : The work builds on previous health and exposure theme, and applied the standards developed for on-site exposure assessment, and measurements of non-sinusoidal waveforms encountered in ISM environments.			
Risks: At present, very little has been done on dosimetry in the THz region, so that limited instrumentation and reference standards are available. Some phantom mixes are presented in the literature for 100 GHz, but the suitability at higher frequencies is not known.			
Knowledge Transfer and Exploitation: A best-practice guide on on-site exposure assessments in ISM environments will be written, and will feed into draft European standards (EN-50413). Provision of measurement service for stand-on current meters. Three Journal papers with collaborators, and involvement of other research groups and SMEs.			
Co-funding and Collaborators: London Centre for Nanotechnology, University College London. The Health Protection Agency,			
Deliverables			
1	**Start: 01/01/2013**	**End: 30/06/2014**	**Cost:**
Standards for assessing exposures for industrial and medical environments 100 kHz to 110 MHz Calibration of E and H-field meters for non-sinusoidal waveforms, calibration of band-selective field meters, calibration of induced current mats			
2	**Start: 01/01/2013**	**End: 31/12/2014**	**Cost**
Standards for assessing exposures for industrial and medical environments: 18 GHz – 3 THz Metrology for THz dosimeter through development of field measurement instrumentation and cell observation protocols			
3	**Start: 01/06/2014**	**End: 31/12/2015**	**Cost:**
On-site exposure assessment for industrial, scientific and medical environments: Methods and models for rapid on-site exposure assessment in industrial and medical environments.			
4	**Start: 01/01/2014**	**End: 31/12/2014**	**Cost:**
Observe non-thermal interactions of terahertz with living cells, normal and cancerous.			

Project No.	EMT 13026	Price to NMO	£142k
Project Title	**Cofunding for TSB project Sub-Surface Produce Imager Utilising Microwave Technologies**	Co-funding target	£142k (secured)
Lead Scientist	Richard Dudley	Start Date	1/4/2013
Scientist Team		End Date	1/3/2015

Summary

Current methods for examining the sub-surface quality of a food product are both destructive and can only be conducted on a small sample, potentially impacting a large batch. A microwave imager offers a step change in testing and leads to a food processing chain with minimal waste, greater testing and thus maximum utilisation and financial return from the raw product. This project will adapt microwave imaging technology from the medical and security markets for deployment into the food processing industry, creating a system that can produce safe 'x-ray like' views inside individual and conveyor belt quantities of fruit, vegetables and packaged product.. The partners will deliver a bench top imager for single item inspection and progress to a conveyor belt system for multiple item scanning supported by the technology Strategy Board Project.

The Need

Without instrumentation to observe the sub-surface condition of raw produce the only method is to cut and quantify a sample of the produce, often implemented in excess of five times from field to market. Currently un-quantified level of waste is created by incorrect sampling during testing, condemning a crate of produce for example when 50% of its contents are perfect. There is therefore a requirement to automate this processing saving time, reducing waste and ensuring quality.

The Solution

The aim is to develop a calibrated imager system. Firstly, the imager will target waste reduction from both the quality testing process and resulting from any subsequent incorrect identification. Secondly, we believe that sub-surface measurements of fruit and vegetable raw product, without destructive testing, offer a key enabler for the next steps in food processing and automation. Existing sub-surface quality control and sorting are entirely manual, the imaging technology in this project will lead to automation of the process and even greater raw product utilisation. Thirdly, accurate identification coupled with higher speed testing will have a direct impact on the logistics and distribution efficiency of a food supply chain.

Once the imager technology is on-line it will be possible to undertake calibration tests to observe how the density, water distribution and structure of raw produce relate to its shelf life. Tests can be extended to processed and frozen foods and a relationship between physical structure and freshness established. This is a speculative side-potential of the imager, but highlights what new approaches can explored with a technology not currently available

Project Description (including summary of technical work)

Overall the project has two main phases:

1. Bench Top Imager. Project plan (i) Use existing imagers from the consortium in laboratory environment to measure four types of raw product, calibrating the technique's sensitivity. (ii) Design and build imager antenna geometry to match required imaging resolution and maximise easy of operation. (iii) Construct final prototype imager system and perform in-field trials using the consortium's supply chain. (iv) Commercialise.

2. Gantry Mounted Imager. Project plan (i) Identify most suitable technology from bench top imager to be deployed as a larger stand-off gantry based imager. (ii) Construct prototype imager in laboratory environment. (iii) Undertake testing and calibration program with imager using test objects use in the bench top system. During this stage the resolution, sensitivity and rate of measurement for a gantry system will be determined. (iv) Patents will be filed at this stage if applicable. (vi) Design an effective deployment of the solution(s) into the agricultural environment which should match current working practices as closely as possible.

NPL's role in the project is to develop one of the two key microwave imaging technologies (following on from the successful cauliflower imager). One experimentation and testing with is complete to select the best technology NPL will specify the equipment for accuracy, resolution, operating distance and speed of image acquisition, and a summary of constraints (dust in the air for example). NPL will provide robust provide characterisation across the project.

Impact and Benefits
The retail sales value (RSV) of fruit and vegetables in the UK is £10.8 bn and corresponds to 8 million tonnes of raw produce. Destructive quality control testing between the farm and shelf accounts for approximately 0.5 % wastage in the post-harvest volume with a net value in excess of £10 Million.

Further positive economic and environmental benefits result from greater utilisation. If raw produce is fully utilised the savings are reflected in the resources used in the crop lifecycle (water, fertiliser, pesticides, fuel, transport, ...). Maximising the return from an acre of farmland is intrinsically linked to the food processing cycle; processing improvements will filter to the farm to ensure the harvested product meets the different retailer's requirements without complex farm resource input. The economic impact to the food processing community of the imaging technology will be a maximum use of raw product and greater confidence in quality control. The improved control of raw product classification will have benefits for the wider society, as pricing fluctuations will have the potential to be reduced and greater wealth held within the UK food sector.
Socially, a 5 year analysis of customer complaints shows that foreign body and internally damaged produce accounts for the second most common category of complaint. Creating fruit and vegetables that meet consumers sometimes unreasonable levels of expectation, will result in a population that eat better and are healthier.

Support for Programme Challenge, Roadmaps, Government Strategies
The project supports the NMS strategy objective to deliver "measurement for food science and technology" in the sustainability challenge.

Synergies with other projects / programmes
The project aligns with the concurrent project TS003 - 1.5 Microwave Imaging.

Risks
The main technical risk is that the resolution / image quality is not adequate to visualise defects in sufficient detail for the application. The resolution is likely to depend on many factors, including the dielectric permittivity of the material medium being imaged and the range/distance between produce and sensor.
Across the whole project, the main risk is that the partners do not have the resources to deliver their parts of the projects or do not work together in a collaborative way. Many risks are mitigated by effective project management and coordination.

Knowledge Transfer and Exploitation
The aim is that NPL's partners will exploit the R+D through commercialisation of the imaging systems and in this particular case knowledge transfer from NPL will be direct through the collaboration. The generic technical knowledge that NPL gains can be used in other projects and the experience of working closely with the partners strengthens our ability to develop instrumentation systems with other UK companies.

Co-funding and Collaborators

Deliverables

1	**Start: 1/04/13**	**End: 31/03/15**	**Cost:**

Deliverable title: Cofunding for TSB project Sub-Surface Produce Imager Utilising Microwave Technologies
Evidence: Meet requirements of TSB grant, including technical, financial delivery and exploitation plan.

Project No.	EMT 13027	**Price to NMO**	£100k
Project Title	**Room Temperature Continuous Maser Development**	**Co-funding target**	
Project Lead	Mira Naftaly	**Start Date**	01/01/2013
Project Team	Rob Ferguson, Conway Langham Mark Oxborrow (Imperial College)	**End Date**	31/12/2013

Summary

In a previous proof-of-concept project, a low-noise, room temperature, solid-state molecular intersystem crossing (MISC) maser was shown to be feasible in pulsed mode. See www.nature.com/uidfinder/10.1038/nature11339 for the basics. This project supports a collaborative effort with Imperial College to develop the technologies towards exploitation by developing the systems and metrology required for continuous operation, improved fabrication for reduced size, and ultra-low noise testing of these maser systems and materials.

The Need

Improved microwave amplification systems would be advantageous to important applications such as telecommunications, astronomy, radar, medical imaging, chemical analysis, scanning for weapons or drugs, all of which can involve the detection of very weak microwave electromagnetic signals. In these applications, lower noise amplification means greater measurement sensitivity and precision, or a shorter measurement time at the same sensitivity/precision. Very low noise microwave solid-state amplifiers typically involve running at cryogenic temperatures and using strong magnets. Our maser amplifier offers substantially lower noise than existing amplifiers operating at room temperature and working on a laboratory bench unshielded in the Earth's magnetic field.

The Solution

NPL will develop the following capabilities and deliver them to the collaboration:

Metrology and scalable fabrication

NPL will design and build a CW optical pump source for the pentacene maser, either as a fluorescence concentrator or other similar functionality. This will be based on rare-earth doped crystal or fibre and will conform to the design requirements of the maser cavity. NPL will also explore candidate materials for the core toroid of the maser, the requirement for which is high dielectric constant and low loss.

Characterizing the performance of extremely low-noise room temperature maser amplifiers (year 2) . Although this is a tough measurement challenge NPL can exploit its existing expertise in rf metrology to produce testing rigs and validate methodologies to measure noise figure, intermodulation distortion, and 1/f noise at L-band at high levels of sensitivity. This will particularly critical in the evaluation of the performance of a CW maser amplifier.

Project Description

The goal is to collaborate with Imperial College to demonstrate and characterise continuous operation of a room-temperature maser by improving the current design and performance as follows:

Design and build a fluorescence concentrator to couple optical pump light efficiently into the active material.

Explore improved design for the dielectric ring holding the active material.

Explore techniques which can potentially enhance continuous operation of a room-temperature maser by actively clearing the lower maser level of population.

Explore techniques which can potentially shift the centre of the maser's peak output frequency (in particular to the microwave emission frequency of hydrogen).

Impact and Benefits

The uptake of low noise maser amplifiers will translate into applications such as healthcare, security, the earlier detection of disease, the timely interception of weapons, the determining beyond doubt that an athlete has taken a performance-enhancing drug. Other external beneficiaries could include the Square Kilometre Array consortium for testing the performance of the Low Noise Amplifiers chosen for installation on its receiving dishes/antennae.

Support for Programme Challenge, Roadmaps, Government Strategies

The project supports the NMS objective to "boost innovation through exploiting the link between measurement science and technological advance" in a very significant way and the technology developed could be key to realising in the longer term the aims in the NMS Growth Challenge: "Focus the NMS investment on measurement technologies that will assist UK business to be innovative".

Synergies with other projects / programmes
Low noise amplifiers and sources are needed in noise measurements at rf and microwave frequencies. Thus potential beneficiaries reside in collaborations with the RF and Microwave group and materials groups within NPL.

Risks
There is a risk is that CW masing cannot be obtained in a molecular system of this kind. This may be because the required pump threshold cannot be maintained continuously or for some other reason not yet understood. There is also a risk that the maser's noise temperature in continuous operation will not be as low as anticipated for reasons not yet understood. This is a challenging project where the outcomes are very uncertain.

Knowledge Transfer and Exploitation
NPL will continue to exploit its existing patent in this area and develop with the collaborators relationships with partners that will eventually lead to the production of commercial systems.

Co-funding and Collaborators
NPL and Imperial College will work in close collaboration.
Also future collaborations with international researchers are possible, with potentially world-wide applications.

Deliverables

1	**Start: 01/01/2013**	**End: 31/12/2013**	**Cost:**
Deliverable title: Demonstration of CW operation **Evidence:** results submitted to peer reviewed journal			
2	**Start: 01/01/2014**	**End: 31/12/2014**	**Cost:**
Deliverable title: Maser noise temperature **Evidence:** Measurement of maser noise temperature (plus gain and bandwidth) published in peer reviewed journal			

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Technical Theme

Time and Frequency Metrology

Science Area Leader

Patrick Gill

Project No.	EMT 13001	Price to NMO	£1180k
Project Title	**Operation of the National Time Scale**	**Co-funding target**	
Project Lead	Peter Whibberley	**Start Date**	01/04/2013
Project Team	John Davis, Setnam Shemar, Peter Whibberley	**End Date**	31/12/2015

Summary This project covers the operation of all of the Time facilities at NPL, including the atomic clocks that form the national time scale, the satellite-based time and frequency transfer links to other NMIs, and the dissemination of time and frequency to in excess of 1 million users across the UK. It also provides for the upgrading of key aspects of the facilities to maintain NPL's position as one of the leading frequency and time labs in Europe, the continued development of clock analysis methods, and the installation and commissioning of an ACES (Atomic Clock Ensemble in Space) Microwave Link ground station to position NPL to participate fully in the optical clock comparisons and other measurement campaigns that will be carried out when the ACES system (due for 2015 launch) is fully operational.

The Need The national time scale UTC(NPL) plays a core role in the NMS, providing the UK contribution to the global time scale UTC and the top-level reference for time and frequency measurement in the UK. It is essential that this capability remains at the leading edge, with a maser-based time scale closely steered to UTC using caesium fountain results, and linked to other NMIs by both two-way satellite time and frequency transfer and carrier-phase GNSS methods. The rapid development of optical clocks and of new satellite and fibre-based frequency and time transfer techniques promise substantial improvement in the generation and comparison of time scales.

The Solution The project will deliver the UTC(NPL) time scale, a continuous, traceable and highly stable reference for time and frequency measurement in the UK. The capability will be enhanced through a series of major development tasks, including steering of UTC(NPL) to UTC based on Cs fountain data, in addition to the installation of a UK Space Agency funded ACES Microwave Link terminal at NPL and investigation of time transfer over an installed dark optical fibre.

Project Description This project covers a broad range of associated activities, including:
- Continuous operation of the national time scale UTC(NPL), steered closely to UTC using NPL Cs fountain results;
- Continuous operation and development of both GNSS and 2-way satellite time & frequency transfer links;
- Dissemination of accurate, traceable T&F to UK users by the MSF radio signal and the computer time services;
- Development of algorithms and analysis methods for atomic clock prediction, time scale generation and time transfer data, and implementation in operational software;
- Enhancements to time and frequency transfer links by automated analysis of measurements and by installing additional systems to allow intercomparisons and increase resilience;
- Installation of an ACES Microwave Link terminal at NPL and development of data analysis methods including relativistic effects;
- Extension of current work on fibre time transfer to performance evaluations over 20-100 km installed dark fibre links.

Impact and Benefits The project will continue to deliver reliable and traceable T&F, essential for UK industry and business, through a range of services, including the MSF radio time signal with in excess of 1 million users and the internet time service. It will provide a substantial contribution to the international time reference UTC and will support the Galileo system timing infrastructure. It underpins NPL leading-edge research that requires access to highly stable and traceable frequency. The development activities will secure the status of the UK in time and frequency metrology by ensuring that NPL retains leading edge capabilities. The combination of an ACES Microwave Link terminal at NPL, fibre transfer capability, and improved analysis methods that allow comparisons of NPL's Cs fountain primary frequency standard and optical clocks with those at other NMIs position NPL as one of the international leaders in time dissemination.

Support for Programme Challenge, Roadmaps, Government Strategies The project is closely aligned with the EMT programme T&F roadmaps and strategy. It has strategically vital roles in providing the core UK contribution to the international time scale and in maintaining the physical representation of that time scale as the source of traceability for T&F measurement in the UK. It also provides for UK representation on relevant international committees, such as ITU meetings aimed at deciding the future of the leap second.

Synergies with other projects / programmes The time scale project underpins all activities at NPL that require a stable reference frequency traceable to UTC, eg many of the electromagnetic standards and measurement services, and the Cs fountain primary frequency standard, femtosecond combs, fibre transfer, trapped ion optical clock and optical lattice clock projects. It provides frequency transfer links between NPL and other NMIs that also contribute Cs fountain data to the BIPM and for comparisons of optical clocks at the 10^{-15} level. The project will support EMRP projects already being funded on fibre transfer and ion clocks, and a proposed EMRP project, currently being evaluated, on international timescales with optical clocks.

Risks The masers forming the national time scale are all old (7, 10, 17 and 22 years as of 2012) and there is a significant risk of multiple failures. The possible need to purchase replacements at short notice has been identified.

- The time & frequency transfer links are based on one TWSTFT system and one dual-frequency GPS receiver, with no redundancy against hardware faults. Additional systems are planned.
- The Time labs have experienced losses of temperature control and water ingress, which will be mitigated by temperature-controlled enclosures for the most sensitive equipment and by flood alarms and prevention measures.

Knowledge Transfer and Exploitation Dissemination to users of precise T&F in the UK is achieved through the MSF radio time signal, internet and dial-up computer time services, and UKAS-accredited services for frequency standard characterisation and GPS common-view time and frequency comparisons. In addition, a much broader range of users of precise frequency and time will benefit indirectly from NPL's regular contribution to the generation of UTC. Aspects of the project work will be exploited by third-party projects in areas such as GNSS monitoring, pulsar navigation, and secure communications. Regular presentations will be given, and articles published in NPL newsletters. The Time pages receive the largest number of hits on the NPL web-site, and will be updated regularly. Technical work will be presented at conferences and published in peer-reviewed journals. In addition, NPL is exploring provision of traceable time to the financial services sector via fibre-based systems. This should cater for new users for whom the MSF signal does not provide sufficient precision.

Co-funding and Collaborators Co-funding is being received from INRIM (~25 kEuro pa) for provision of UTC(NPL) data to the Galileo Time Validation Facility. Contributions will be made to a proposed EMRP JRP on "international timescales with optical clocks", and to JRPs on "optical clocks with trapped ions" and "fibre time & frequency transfer". Close collaboration with UCL on GNSS satellite clock data analysis developed through the NMS 2009-12 Space Clocks project will be developed further. Other collaborators include Chronos Technologies, the General Lighthouse Authorities and the University of Bath on GNSS and LF signal monitoring. The project will benefit greatly from UK Space Agency awards of £500k for a dark fibre link between NPL and Harwell, and £440k to procure an ACES Microwave Link ground terminal for NPL.

Deliverables

1	**Start: 01/04/13**	**End: 31/12/15**	**Cost:**

Operating the national time scale: Continuous operation of the UTC(NPL) national time scale and at least one time transfer link throughout the project. Regular contribution of clock and time transfer measurements to the BIPM for use in generating UTC, and provision of stable and traceable frequencies to NPL users. Operation of remote frequency transfer links to compare NPL Cs fountain PFS and optical frequency standards with those at other labs. At least one calibration of NPL's time transfer links will be carried out during the 3 years. Representation by NPL scientists on relevant international committees including CCTF and its working groups, ITU-R meetings (including WRC, SG7 and WP7A) and the EURAMET Time and Frequency Technical Committee.

2	**Start: 01/04/13**	**End: 31/12/15**	**Cost:**

Time dissemination services: Continuing provision of time dissemination services, including monitoring and control of the MSF 60 kHz radio time signal, operation of the internet (NTP) and dial-up time services for computers, off-air monitoring of time signals available in the UK, and information for service users made available on the NPL web site. Monitoring will be extended to include the Anthorn eLoran signal, and the computer time services will be extended to include authenticated NTP and PTP services if there is sufficient customer interest.

3	**Start: Start: 01/04/13**	**End: 31/12/15**	**Cost:**

Development of time scale facilities: The Time facilities will be upgraded to maintain NPL's position as one of the leading Time labs in Europe through a rolling programme of development tasks. These are:
2013: 1) Enhancing the time scale generation to achieve UTC-UTC(NPL)<5ns (1σ) for 95% of the time by using rapid UTC and Cs fountain data; 2) assembly, commissioning and calibration of a second TWSTFT earth station for experimental work and resilience against failures; 3) procurement, commissioning and calibration of a second dual frequency GNSS receiver with Galileo capability.
2014: 1) Design and procurement of temperature-stabilised enclosures for the masers; 2) Development of operational clock monitoring and error detection software based on clock prediction algorithms.
2015: 1) Commissioning TAI-PPP software to analyse carrier-phase GNSS data; 2) replacement of the old, failing MSF monitoring equipment.

4	**Start: Start: 01/04/13**	**End: 31/12/15**	**Cost:**

ACES Microwave Link at NPL: Procurement (using committed UKSA funding) of an Atomic Clock Ensemble in Space (ACES) Microwave Link (MWL) ground terminal, with installation at NPL expected during early 2014. Development of novel analysis methods and software to process data from the MWL ground terminal, focusing in particular on general relativistic effects to perform optimal ground-space and ground-ground clock comparisons.

Project No.	EMT 13002	**Price to NMO**	£268k
Project Title	**Optical Lattice Clock**	**Co-funding target**	
Project Lead	Anne Curtis	**Start Date**	01/04/13
Project Team	Anne Curtis, Yuri Ovchinikov, Ian Hill, Richard Hobson (NPL Industrial Case student from Oct12), Patrick Gill	**End Date**	31/12/13

Summary The goal of this project is to develop a world-class optical clock based on neutral atoms held in an optical lattice. This capability is necessary to position NPL in anticipation of a possible redefinition of the SI second based on lattice clocks. This standard will feed into the optical frequency infrastructure of the T&F group via the femtosecond combs project, enabling us to assess systematics and perform NPL in-house optical-optical comparisons and contribute to international comparisons.

The Need NPL needs to be in a globally competitive position if the SI second is redefined in terms of a neutral atom optical standard. It is therefore necessary to achieve comparable results to other world-leading NMIs. The current best absolute frequency measurement of the ^{87}Sr isotope clock transition in neutral Sr was made at JILA with an error of 8.6 x 10^{-16}, which is presently the most accurate measurement of any optical frequency standard based on neutral atoms. In addition, the systematic uncertainty of the lattice clock contribution to this measurement was only 1.5 x 10^{-16}. The assessment of the systematics of the lattice clock was made possible using a fibre link between the strontium clock at JILA and the calcium neutral atom frequency standard at NIST. Furthermore, measurements made during the past few years in Japan, the US, and France agree at the part in 10^{15} level. This high level of reproducibility makes a strong case for neutral Sr Lattice clock to be adopted as the new definition for the SI second.

The barrier to improving uncertainties to a level better than a part in 10^{16} is the systematic error due to the shift of the clock frequency in the presence of blackbody radiation from the room temperature vacuum chamber surrounding the atomic sample (BBR shift). Only theoretical values for this shift have been derived. To make progress in reducing the overall uncertainly of Sr lattice clocks, this frequency shift needs to be experimentally determined. In addition, microwave-based standards do not average down fast enough for optical standards to use them to track down systematics at the less than a part in 10^{16} level. A system with better short-term stability is required to ascertain and correct for systematic frequency shifts of the clock transition at this level and on a reasonable experimental timescale. Neutral atom clocks have an advantage over ion clocks in terms of short-term stability; this can help in addressing systematic effects. In this regard NPL's developing capability in neutral atom optical clocks will also provide additional benefit to the single ion optical clock projects, via femtosecond combs and universal synthesizer linkages.

The Solution At NPL we have both single ion and neutral atom optical frequency standards under one roof and will be able to use excellent short-term stability of the neutral atom standard to benefit both types of clock in the way that drove optical frequency comparisons at JILA and NIST. Furthermore, by utilising collaborations with other NMIs in Europe (facilitated by EMRP Joint Research Projects and the EU FP7 SOC2 project) we can greatly increase the speed of progress. Our contribution to reducing the overall uncertainty of Sr lattice clocks through our measurements of the BBR shift will allow us to make high-accuracy measurements of the strontium clock transition frequency and ratios of optical frequencies at NPL. Comparing those measurements to ones made at various other NMIs will give greater strength to the option of using neutral strontium as a basis for the next redefinition of the SI second.

Project Description This project builds on the work of the current NMS Lattice clock project at NPL. We are preparing for a frequency measurement and basic systematics analysis of the ^{88}Sr clock transition in neutral Sr held in an optical lattice, which should be completed by Dec 2012. Then, the experimental system will be re-organised to measure the clock transition in the preferred but more complex ^{87}Sr isotope. This will include building additional laser systems at 689 nm.

One major goal of this project is to provide an experimental measurement of the blackbody radiation shift in neutral Sr. An apparatus for creating a controllable blackbody environment has been developed during the current programme. In Deliverable 1 we will be testing the transport of cold atoms into and out of this blackbody device and making measurements of the frequency shift due to a change in temperature of the environment. We will perform a complete assessment of all systematic uncertainties in the lattice clock experiment and perform an absolute frequency measurement of the ^{87}Sr clock transition – the first such optical frequency measurement made at NPL with neutral atoms. We expect to reach an uncertainty of 1 x 10^{-14} or better for this initial frequency measurement using NPL's femtosecond comb referenced to our maser system.

Deliverable 2 aims to achieve a measurement uncertainty due to the Sr lattice clock system at the part in 10^{15} level. This will be attained making interleaved measurements (changing experimental parameters between measurements) and comparing the measured frequencies to assess changes due to systematic effects. Once the systematics are assessed at the part in 10^{15} level, the system will be ready for absolute frequency measurements and frequency ratio measurements against the ion optical clocks at NPL, as outlined in the proposed EMRP project on optical clock comparisons (ITOC). Additionally, we propose to theoretically explore the use of quantum entanglement to improve the stability of lattice clocks, with a focus on future experimental implementation.

In order to explore the uncertainty of the system at a level better than a part in 10^{15} it becomes necessary to measure systematic effects using an additional optical frequency reference beyond the single standard we are currently building. One option is to use the accuracy and stability of one of the NPL ion clocks as the reference via a femtosecond comb to assess the systematics. However, there would likely be limitations in the rate of progress due to time and resource logistics across 3 separate projects. A better solution would be to build a second Sr lattice experimental system in the lattice laboratory, which is a possible direction for work beyond this project. We could then assess and reduce the systematic uncertainties without needing to use the fs comb or other clock systems, but instead monitor frequency changes by measuring the beat frequency between our two clock lasers, each of which would be independently locked to a different Sr lattice clock apparatus.

Impact and Benefits The importance of the BBR shift measurement cannot be overstated, as this is currently the largest systematic in the lattice clock system that has not been properly experimentally verified. Our measurements will assess the validity of the theoretical model and be applicable to all Sr lattice clock systems currently being developed. Our development of a neutral atom lattice clock anticipates future NMS requirements that may stem from the redefinition of the SI second in terms of an optical frequency. This work is feeds into ESA and EU Framework 7 optical atomic space clock development programmes.

Support for Programme Challenge, Roadmaps, Government Strategies The NMS strategy includes the goal of developing optical clocks with a part in 10^{17} uncertainty.

Synergies with other projects / programmes To keep on track with NPL and European roadmaps it is essential to utilize the synergy between the neutral atom and ion clock optical standards at NPL in order to continue our work towards improving their uncertainties. The growing metrology infrastructure in the group will allow for intercomparisons of the different optical standards for sytematics assessment and accuracy evaluations at the highest level, as has been shown to great benefit at other NMIs.
The fs comb project (or universal synthesizer project) is essential to all frequency measurements to be made in this project and for simultaneous measurements and comparisons of more than one optical frequency standard.

Risks There is a chance that results achieved during Deliverable 1 or 2 may indicate the need for a change in a major subsystem of the experiment (laser system or vacuum system) due to presently unexplored effects on the systematic uncertainty of the Lattice Clock system. To cover for this possibility we have purposely extended Deliverable 2 to over 1 year, but there may still be some delay due to the unknown nature of the changes potentially necessary in the rebuild of the experimental system.

Knowledge Transfer and Exploitation Publishing results in high-profile journals: Physical Review Letters, Optics Letters and invited oral and poster presentations given at major international conferences.

Co-funding and Collaborators Current co-funding from SOC2 project (92k€, 2011-2013), collaboration on EMRP ITOC JRP

Deliverables

1	**Start: 01/04/13**	**End: 31/12/13**	**Cost:**

Deliverable title: 87Sr frequency measurement
87Sr frequency measurement with BBR measurements and systematics analysis, uncertainty at the 5 Hz level, ~1x10-14

2	**Start: 01/10/13**	**End: 31/12/14**	**Cost:**

Deliverable title: Improvement of systematic uncertainties
Improvement of systematic uncertainties to the part in 10^{15} level. This will be attained by making interleaved measurements (changing experimental parameters between measurements) and comparing the measured frequencies to assess changes due to systematic effects. In addition, theoretical investigation of quantum entanglement as a route to improving the stability of lattice clocks, with a focus on experimental implementation.

Project No.	EMT 13003	**Price to NMO**	£967k
Project Title	**Trapped Ion Optical Frequency Standards**	**Co-funding target**	
Project Lead	Hugh Klein	**Start Date**	01/04/2013
Project Team	Geoff Barwood, Rachel Godun, Guilong Huang, Peter Nisbet-Jones Steven King, Hugh Klein and Patrick Gill	**End Date**	31/12/2015

Summary Optical frequency standards offer an improvement of almost two orders of magnitude in the ability to realise the SI second and a redefinition is likely within the next five to ten years. They also enable tests of fundamental physics, such as the stability of the fine structure constant and will support practical terrestrial and space applications. This project will develop state-of-the-art optical frequency standards based on both single and dual-ion systems. The aim is to improve the existing reproducibility and stability of the NPL single ion systems, targeting the few 10^{-17} level. Within the project, NPL will also develop a dual-ion sympathetically-cooled Al^+ linear trap system to take advantage from the quantum logic clock technology based on this system, should it continue to offer leading performance and become a preferred option for a redefinition.

The Need The best optical clocks now exhibit better performance than Cs fountain primary microwave standards, but are limited by absolute reference to the fountain. An "optical" redefinition of the SI second will resolve this difficulty; an evaluation of the potential candidates is needed so that a choice can be made. Frequency comparisons between two Al^+ optical clocks at NIST have evaluated systematic effects with an uncertainty at the $8.6\text{x}10^{-18}$ level. At JILA (USA) and SYRTE (France) evaluations of the uncertainty of strontium atom based optical lattice clocks are at the 10^{-16} level. Projections suggest that the best ion trap based optical clocks will continue to be more accurate than atom lattice clocks although these are expected to have better short term stability. At NPL and PTB octupole and quadrupole transitions in Yb^+ have been studied with the best uncertainty of 8×10^{-16} limited by the Cs fountain with systematic evaluations at the $7\text{x}10^{-17}$ level. These measurements demonstrated the best international agreement between trapped ion optical frequency standards. Studies of Sr^+ at NPL have demonstrated stabilities at the 10^{-16} level; we expect most systematic effects to be evaluated at or below this level during the next 3 years. These kinds of studies feed into tests of physics and fundamental constants both on the ground and in future space missions, in particular the stability of the fine-structure constant. Optical frequency standards will contribute to future timescales. Future space uses include mapping of the earth's geoid, improved satellite navigation and associated commercial applications and critical infrastructure, together with provision of space-based master clocks for remote ground clock comparison. The long term strategic practical importance of this technology is a strong reason for NMS funding of this project. It will enable the UK to maintain NPL's position as a top NMI, capable of influencing the redefinition of the second, with the ability to rapidly realise the new standard.

The Solution This project will develop state of the art optical frequency standards based on both single and dual-ion systems. The Yb^+ 467nm octupole transition has been shown to possess particularly low sensitivity to magnetic field and electric field gradients. Ratio measurements between the octupole transition and a 436nm quadrupole transition in a single Yb^+ ion will allow a constraint to be placed on the time-variation of the fine structure constant. The Al^+ system has a suitably narrow optical clock transition at 267 nm which has the lowest sensitivity known to "black-body" shifts making it an attractive species for future study. However it cannot be directly laser cooled because at present no cw laser sources reach the required deep UV cooling transition, however sympathetic cooling is possible. A dual-ion system will be developed to allow sympathetic cooling and quantum logic readout of Al^+ via an auxiliary ion.

Project Description

1. The evaluation and reduction of systematic effects in NPL's existing single ion systems will be carried out targeting reproducibility and stability at the few 10^{-17} level. Appropriate Cs-limited absolute frequency and frequency ratio measurements will be carried out in conjunction with two EMRP projects.
2. Periodic measurements will be made of the ratio between the 467nm octupole transition and a 436nm quadrupole transition in a single Yb^+ ion, which has the largest known sensitivity to the time-variation of the fine structure constant. These will place a limit on the stability of the fine structure constant initially at the 10^{-16}/year level and in three years at the 10^{-17}/year level.
3. A new linear dual-ion trap system based on a micro-fabricated design (developed within a previous pathfinder project) is envisaged together with the development of the two required stable 267 nm radiation sources (for motional state transfer and probing) and a photoionization laser at 396nm. Fundamental lasers for a frequency quadrupling system will be stabilised to ULE vibration insensitive cavities.

Impact and Benefits Ultra-stable optical frequency standards offer the route to measuring time with the highest level of accuracy and contribute to the international time scales TAI and UTC. There is already the formal opportunity for trapped ion and atom optical secondary representations of the second to input data to TAI. Trapped ion optical clocks offer benefits to both fundamental physics and technology. Very high precision measurements of certain trapped ion frequency ratios will have impact on basic science, specifically in the testing for the time-variation of a fundamental constant. Future technology wider impact benefits include improved and more secure satellite navigation systems incorporating optical clocks, and higher accuracy time and frequency transfer between remote locations.

Support for Programme Challenge, Roadmaps, Government Strategies This project is strongly aligned to the time and frequency roadmaps for the EMT programme. Redefinition of the second – a key SI unit, is anticipated within the next decade and this is an objective of the NMS strategy. It is vital for the government to refine its capability in this area so that the UK continues to be among the world leaders and able to influence international decisions.

Synergies with other projects / programmes This project links with two other EMRP projects described below and with several of the other time and frequency theme projects, in particular: optical lattice clocks, primary frequency standards, and universal synthesiser.

Risks Deliverable 4: A low heating rate in the micro-trap will be required for Sr^+ to be suitable for sympathetic cooling.
Deliverables 3-7: Several capital equipment items will need to be purchased in a timely fashion, including: a high sensitivity camera, a micro-trap system, the lasers (1068nm,1070nm and 396 nm) and two quadrupling systems for 267nm.

Knowledge Transfer and Exploitation The outputs of the project will be disseminated primarily by publications in peer-reviewed journals, presentations at leading international conferences, and reports to international committees such as the CCTF and the CCL-CCTF joint working group on frequency standards.

Co-funding and Collaborators EMRP SIB04 "High-accuracy optical clocks with trapped ions", 1st May2012 – 30th April 2015, collaborators: PTB, CMI and MIKES. EMRP SRT-s20 "International timescales with optical clocks", 1st July 2013 – 30th June 2016. All partners (CMI, INRIM, MIKES, OBSPARIS, PTB) are strongly committed to the project; they consider that it is important for the European time and frequency metrology community and it has support from the CCTF chair.

Deliverables

1	**Start: 01/04/13**	**End: 31/12/14**	**Cost: £**
Cs-limited absolute frequency measurement of a trapped ion optical frequency standard: incorporating improved magnetic field control and reduced clock transition linewidths.			
2	**Start: 01/04/13**	**End: 31/12/15**	**Cost:**
Constraint on time-variation of the fine structure constant at the level of 10^{-17}/year: via periodic comparative measurements of the 467nm and 436nm transitions in Yb^+.			
3	**Start: 01/07/13**	**End: 30/12/14**	**Cost:**
Development of stable lasers at 1068nm and 1070nm and a 396nm source: for Al^+ motional state transfer, probe and photo-ionization radiation generation respectively.			
4	**Start: 01/01/14**	**End: 31/12/14**	**Cost:**
Trapping of a sympathetically cooled Al^+ ion: in a linear micro-trap using Sr+ or best matched cooling ion.			
5	**Start: 01/07/14**	**End: 31/12/15**	**Cost:**
Quadrupling systems for 267nm transfer and probe radiation: via two pairs of doubling stages.			
6	**Start: 01/01/15**	**End:31/12/15**	**Cost:**
Demonstration of performance at the fewx10^{-17} level in a single ion frequency standard: by evaluation and reduction of systematics			
7	**Start: 01/01/15**	**End:31/12/15**	**Cost:**
Zero-point cooling of Al^+ and evaluation of readout options: including quantum logic.			

Project No.	EMT 13004	Price to NMO	£529k
Project Title	**Co funding for EMRP ITOC SIB55-International Timescales with Optical Clocks**	Co-funding target	£400k in place
Project Lead	Helen Margolis	Start Date	01/07/2013
Project Team	Rachel Godun, Luke Johnson, Anne Curtis, Hugh Klein, Peter Whibberley, Setnam Shemar, Patrick Gill	End Date	30/06/2016

Summary Integration of optical atomic clocks into the international timescales TAI and UTC is a key prerequisite for a future redefinition of the SI second. The vision for this project is a coordinated programme of intercomparisons between European optical clocks at a level limited only by the systematic uncertainties of the clocks themselves. Such a programme will allow the full potential of the clocks to be realized and will enable NPL (as coordinator) and other European NMIs to play an influential role in international debates concerning a redefinition of the second. In the shorter term, optical clocks will enhance the stability of international timescales, benefiting applications in navigation, communications, geodesy and fundamental science.

The Need The best optical atomic clocks now clearly surpass the stability and accuracy achievable with microwave clocks and an optical redefinition of the second is being actively considered. Although certain optical clocks can in principle be used as secondary representations of the second, none are yet contributing to international timescales in practice.

Currently the international timescales TAI and UTC are constructed using data from microwave atomic clocks in approximately 70 institutions worldwide, compared by satellite time and frequency transfer techniques. Data from Cs primary frequency standards are used whenever available to apply steering corrections, ensuring that the scale interval of TAI and UTC remains as close as possible to the SI second. The best Cs fountain primary frequency standards have accuracies at the few parts in 10^{16} level, with averaging times of several days being required to achieve this accuracy. Optical clocks could therefore enhance the stability of international timescales by an order of magnitude, but their implementation in the timescale requires a series of co-ordinated comparisons of these clocks at different NMIs.

The Solution A framework and procedures for integrating optical atomic clocks into international timescales in preparation for a redefinition of the SI unit of time needs to be established. This will validate their performance levels and build confidence in a future redefinition. Clock comparisons will be carried out both locally within individual NMIs and remotely between different NMIs, supported by essential theoretical work to quantify the relativistic and geodetic effects that influence time and frequency comparisons at this improved level of accuracy, and validated by a proof-of-principle relativistic geodesy experiment.

Project Description Direct comparisons of similar optical clocks will be carried out locally within individual NMIs. Local comparisons of different types of optical clocks will also be carried out by means of optical frequency ratio measurements using femtosecond combs. Target accuracies for these local comparisons will be at the parts in 10^{17} level or better. Absolute frequency measurements of the optical clocks relative to local caesium primary standards will also be performed, since these are essential to maintain continuity with the present definition of the SI second.
Direct frequency comparisons will be carried out between optical clocks in different NMIs using conventional and broad bandwidth satellite time and frequency transfer techniques, fibre links and transportable optical clocks, with target accuracies in the $10^{-16} – 10^{-17}$ range. To support this comparison programme a full evaluation of relativistic effects influencing time and frequency comparisons at the 10^{-18} level of accuracy will be carried out. This will include determination of the geodetic height corrections that need to be applied to the frequencies of the clocks at each partner NMI in order to correct the operating frequencies of the clocks to the values they would have on the geoid.
Procedures will be developed to analyze the frequency ratio measurement matrix derived from the above set of measurements to check their consistency, enabling any issues with individual clocks or gravitational corrections to be identified. Finally procedures will be developed for deriving steering corrections to UTC based on the input from the frequency ratio matrix. To demonstrate one application of improved clocks and timescales, a proof-of-principle experiment will be carried out in which optical clocks are used to measure the difference in gravity potential between two locations approximately 90 km apart and with a height difference of approximately 1000 m.
<u>The work packages that NPL will be most involved in the delivery off are:</u>

- **Local & remote frequency comparisons:** Direct comparison of similar optical clocks, and comparison of different types of optical clocks by means of optical frequency ratio measurements using femtosecond combs, locally within individual NMIs, with target accuracies at the parts in 1017 level or better. Caesium-limited absolute frequency measurements of optical clock transitions. Direct frequency comparisons between optical atomic clocks in different NMIs using satellite links, fibre links and/or transportable optical clocks with target accuracies in the 10-16–10-17 range.
- **Relativistic timescales and geodesy:** Complete evaluation of relativistic effects influencing time and frequency comparisons at the 10-18 level of accuracy, including determination of geodetic height corrections.
- **Relativistic geodesy experiment**: Proof-of-principle experiment using optical clocks to measure gravity potential differences.

- **Algorithms and two-way time and frequency link development:** Investigation of the potential for improved TWSTFT by using the full bandwidth capability of typical transponders provided by communication satellites. Analysis of frequency ratio measurement data obtained from WP1 and WP2 to check consistency. Development of possible procedures for steering of TAI by optical frequency standards.
- **Impact & and project management:** Knowledge transfer & dissemination, project meetings & reporting. (NPL will coordinate).

Impact and Benefits A coordinated programme of comparisons between state-of-the-art optical atomic clocks with performance at the 10^{-17} level will have impact across a range of areas and applications in metrology, science and technology.

- It will benefit the further development and practical utilization of these clocks, allowing the international metrology community to make better informed decisions regarding a future redefinition of the SI second.
- The international scientific community will benefit from validated clock comparisons as a basis for tests of fundamental physical theories such as general relativity. One example is a search for temporal variation of the fine structure constant by comparing transition frequencies in different optical atomic clocks.
- The project will affect Europe's metrology infrastructure on a long-term basis as it will enable time and frequency to be disseminated with unprecedented stability to end users. Users of the international timescales will benefit from their improved stability, for example for applications in navigation and telecommunications.
- The proof-of-principle geodesy experiment will pave the way for a new technique for directly measuring the Earth's gravitational potential with high temporal and spatial resolution. Gravity potential measurements could in principle be made with an accuracy corresponding to a few cm in height at specific locations. Such measurements would complement the data obtained from satellite missions such as GOCE or GRACE, which provide global coverage but give measurements that are spatially averaged over length scales of approximately 100 km. Precise measurements of changes in the gravity potential can provide important information about large-scale mass redistribution phenomena, e.g. related to the hydrological cycle, that enable models of global climate change to be tested and improved.

Support for Programme Challenge, Roadmaps, Government Strategies This project is strongly aligned to the time and frequency roadmaps for the EMT programme and is strategically important in that it will allow NPL (as coordinator) to influence the direction of European research activity towards the introduction of optical atomic clocks into international timescales and a future redefinition of the SI second – akey objective of the NMS strategy.

Synergies with other projects / programmes This project links together most of the other activities within the time and frequency theme (trapped ion optical clocks, optical lattice clocks, primary frequency standards, national timescales, femtosecond combs, time and frequency transfer over optical fibre) to establish a framework whereby optical atomic clocks can be integrated into international timescales. It also links NPL work on optical clocks with similar work being carried out at other NMIs within Europe.

Risks Operating optical atomic clocks with their optimum performance in several NMIs simultaneously will be challenging, but this risk is mitigated by the fact that there is more than one type of optical clock available in three of the NMIs. The proof-of-principle relativistic geodesy experiment relies on the availability of an optical fibre link from INRIM to Modane on the French border, but we have a back-up option of a fibre link between PTB and Munich (height difference 400 m).

Knowledge Transfer and Exploitation Europe, with its critical mass of NMIs and other institutions developing optical atomic clocks, is seen as the ideal region in which to establish an integrated framework which can later be adopted worldwide. The outputs of the project will be disseminated primarily by publications in peer-reviewed journals, presentations at leading international conferences, and reports to international committees such as the CCTF and the CCL-CCTF joint working group on frequency standards. A public workshop for the JRP project will be organized, at which the most important outcomes will be presented to representatives from academic, industrial and policy making organisations.

Co-funding and Collaborators This project will be undertaken in collaboration with other European NMIs (CMI, INRIM, MIKES, OBSPARIS, PTB) and geodesy experts from the University of Hannover as part of the EMRP programme. All partners are strongly committed to the project, since they consider that it represents an important step forward for the European time and frequency metrology community.

Deliverables

1	**Start: 01/07/2013**	**End: 30/06/2016**	**Cost:**

Deliverable Title: Co funding for EMRP ITOC SIB55-International Timescales with Optical Clocks

Project No.	EMT 13005	**Price to NMO**	£560k
Project Title	**Caesium Primary Frequency Standard**	**Co-funding target**	
Project Lead	Krzysztof Szymaniec	**Start Date**	01/04/13
Project Team	Krzysztof Szymaniec, Stephen Lea	**End Date**	31/12/14

Summary

The proposed project will deliver a fully operational and robust system of primary frequency standards for:

- international timescale calibrations (coordinated by BIPM),
- steering and definition of the local timescale,
- accurate absolute frequency measurements (e.g. for optical clocks under development).

The system will consist of the existing, highly accurate fountain standard NPL-CsF2, which will be maintained and operated regularly, and a new standard NPL-CsF3, which is being designed and built using some parts of the prototype fountain CsF1. The two fountains will provide the necessary redundancy for near-continuous operation and allow for direct comparisons in order to verify their declared accuracies.

The Need

A system of accurate (uncertainty of parts in 10^{16}) and robust standards is essential to provide regular evaluations of the international timescale TAI and to support the national (local) timescale UTC(NPL). Only the best NMIs possess the capability to realize the SI definition the second with such accuracy and it is vital that NPL provides the service to international T&F community and indirectly to scores of users worldwide. In addition, the project will support development of the optical frequency standards at NPL by enabling absolute frequency measurements and thus influencing the integration of Secondary Representations of the second into TAI.

The Solution

A system of two independent caesium fountain primary frequency standards, operating robustly with sufficient degree of redundancy will provide regularly throughout the year a reference for time scale calibrations and absolute frequency measurements. It will consist of:

1) NPL-CsF2 standard operated at the current level of accuracy;
2) Fully evaluated new standard NPL-CsF3 (currently being built);
3) Signal analysis infrastructure, links to timescales, and new local oscillator for improved short-term stability.

Both NPL fountains are based on unique design, which is relatively simple and robust, with a single stage MOT as the source of cold atoms, and achieves the highest level of accuracy and potentially very low short-term instability (parts in 10^{14} at 1 s). These two NPL PFS systems together will provide important and enhanced coverage to the steering of TAI/UTC.

Project Description

The project will build on the existing highly accurate NPL fountain standard CsF2 (long term accuracy 2×10^{-16}, one of the best in the world) and a new set-up, CsF3, which is currently being assembled and is expected to achieve similar or better level of accuracy.

Within the proposed project the accuracy of NPL-CsF3 will be fully evaluated and reported. The CsF3 set-up will incorporate improvements recently introduced to CsF2, like the optical pumping to the clock sublevels and will use a new microwave cavity designed in collaboration with Penn State University. As part of the accuracy evaluation, we will attempt for the first time to experimentally verify the effect of microwave lensing (recoil) and a frequency shift due to collisions with residual background gas.

NPL-CsF2 will be operated and maintained at the current high level of accuracy with further work on the detection signal-to-noise ratio improvements. The latter will include implementation of new local oscillator using low noise microwave signal generated by femtoseconds frequency comb or, alternatively by a cryo-cooled sapphire oscillator. A possibility of using light induced atomic desorption (LIAD) for improved MOT loading will be explored. At a later stage, a new, integrated and robust optical bench will be designed and built. Control electronics and software will be updated allowing for more automated operation.

Extensive <u>direct comparisons</u> between the two local PFS systems will be performed aiming to verify particular type B uncertainties and the overall accuracy.

Data from either or both fountain standards will be made available for local and global time timescale calibration (regularly) and for absolute frequency measurements (as needed).

Impact and Benefits

NPL is one of only few laboratories able to calibrate the global timescale, thus impacting on a huge user community (through navigation and IT services, synchronisation of power and telecom grids, time-stamping electronic banking etc).
The project will support basic research eg. optical clocks as well as the current delivery of UK and international timescales.

Support for Programme Challenge, Roadmaps, Government Strategies

Operation of microwave fountain standards is essential to the key NMS objective of delivering UTC(NPL) timescale and for NPL novel frequency standards for optical clocks. It enables basic science (relativistic geodesy, radio-astronomy) and more applied innovation (e.g. satellite and space navigation).

Synergies with other projects / programmes

Operation of national time scale – enables local calibration of the time step interval and short-term disciplining.
Time transfer links – enables links and comparisons with standards overseas, making contributions to global timescale steering.

Femtosecond frequency combs – the microwave reference for comb measurements, and use of the microwave local oscillator signal generated from an optically referenced frequency comb in the evolving Cs fountain.
Ion traps and lattice clocks – the microwave reference for absolute optical frequency measurements.

Risks

The project delivery relies on robust operation of PFS subsystems (diode lasers, electronic control of the experiment) and of the temperature control system in the lab. Improvements of short-term stability rely on deliverables of other projects proposed for funding within the EMT programme.

Knowledge Transfer and Exploitation

The KT activities will include specialist publications in peer-reviewed journals and at conferences as well as presentations for wider audiences. The PFS project enjoys a high level of interest in media and among numerous visitors to NPL, including high profile individuals. There also exist possibilities for technology transfer with interest already being expressed by countries rapidly developing their metrology infrastructure, such as India, china and Poland. Moreover, the leading-edge research involved will feed into other activities closer to direct applications (eg atomic magnetometry, quantum-limited detection)

Co-funding and Collaborators

It is anticipated that the project will benefit from established collaborations with Pennsylvania State University and National Measurement Institutes in Korea (KRISS), China (NIM), India (NPL), and Japan (NMIJ). A secondment scheme is envisaged, where the visitors are financially supported by their home institutions adding significant value to the project.

Deliverables

1	**Start: 01/04/13**	**End: 31/12/14**	**Cost:**

Deliverable title: Contribute to TAI 6 times a year

- Contributions to TAI step interval calibration (min. 6 times per year)
- Provision of data for the steering of the local timescale
- Reference data for absolute frequency measurements of optical frequencies
- Upgrade of optical bench
- Upgrade of control electronics and software (automated operation)

2	**Start: 01/04/13**	**End: 31/12/14**	**Cost: £**

Deliverable title: <u>Accuracy evaluations and performance improvements</u>

- Accuracy evaluation of NPL-CsF3 and re-evaluation of NPL-CsF2
- Implementation of new local oscillator and investigations of limits to short-term stability

Project No.	EMT 13006	Price to NMO	£163k
Project Title	**Next Generation Frequency Transfer Techniques**	Co-funding target	
Project Lead	Giuseppe Marra	Start Date	01/01/2013
Project Team	Giuseppe Marra, Helen Margolis, Luke Jonhson, Maurice Lessing	End Date	31/12/2013

Summary
This project will investigate new advanced fibre transfer techniques for the comparison of optical clocks. The techniques targeted should be cheaper and easier to implement on real networks compared to those already existing and will therefore provide a potential solution for inter-continental frequency transfer. The project is crucial to enable NPL to play a pivotal role in the comparison of optical clocks in Europe and the rest of the world.

The Need
Existing single optical carrier transfer techniques have been shown to meet the accuracy and the long term stability requirements for the comparison of state-of-the-art clocks using many fibre links over hundreds of kilometres. Tests have been successfully run over 540 km of commercial fibre carrying internet traffic and on 920 km of dedicated dark fibre. However, the implementation of these techniques on commercial fibre networks is very demanding in terms of costs and logistics and this has slowed down the transition from laboratory tests to real world implementation. The cost and complexity come from the fact that in these techniques the optical signal travels bi-directionally in order to cancel the fibre noise and this cannot be achieved over standard commercial networks without substantial modification of the equipment setup along the fibre link. For bidirectional propagation, each commercial amplification stage needs to be bypassed and replaced by a custom-built bidirectional amplifier. This not only adds substantial cost, but adds logistical complexity as fibre service providers are often reluctant to grant permission to modify their standard equipment. Another important limitation of existing fibre transfer techniques is that their short term stability performance is linked to the fibre link length. For a 1000 km link, the stability is limited to parts in 10^{14} or worse depending on the environment in which the fibre is installed. This stability level imposes a long averaging time before two state-of-the-art clocks can be compared to their best accuracy. To exploit the full potential of fibre frequency-transfer systems, their costs need to be reduced whilst maintaining their performance at or better than the best optical clocks.

The Solution
An advanced fibre transfer technique that does not require the light to propagate bi-directionally. This could be achieved by measuring the relative phase change between two optical carriers at the user rather than just one returned at the transmitter end. As no returned light is required, standard commercially-available unidirectional optical amplifiers could be used, greatly reducing the complexity and cost for frequency transfer over long fibre links. Also, the stability of the transferred signal should no longer be dependent on the fibre length as in previous bidirectional techniques.

Project Description (including summary of technical work)
Building on successful preliminary tests conducted during the current NMS-programme, in the first year the basic principle, on which the two-carrier idea is based on, will be tested to explore the accuracy and stability limits fully, to establish the performance at longer time scales and over increasingly longer fibre lengths. In the second year a true comparison between two ultra-stable optical references will be carried out using the two-carrier transfer technique over an optical link of at least 100 km consisting of a spooled or installed fibre. In the third year the technique will be pushed forward to a target fibre length of 1000 km.

Impact and Benefits
Developing the first unidirectional fibre transfer technique suitable for the remote comparison of optical clocks will put NPL at the forefront of research in this area and will lead to high-profile peer-reviewed publications. A frequency transfer technique that does not require specially designed amplifiers and that can be performed using existing fibre network infrastructure will make it easier to disseminate ultra-stable frequencies to non-NMI laboratories and industry, helping to create impact for time and frequency measurement technology outside the metrology area.

Support for Programme Challenge, Roadmaps, Government Strategies
This project is strongly aligned with the NMS-funded optical clock development which require frequency comparison capabilities to optical clocks located in other NMIs meeting the NMS strategy objective of “ensuring consistency of international time standards in order to communicate reliably and navigate accurately throughout the world”,.

Synergies with other projects / programmes
The development of state-of-the-art optical clocks at NPL requires new ways of comparing them with those in other European countries, since the performance of satellite-based techniques is insufficient. This project strongly contributes to making clock comparisons between NPL and other European countries easier and less costly to achieve. The project has also strong synergy with the EMRP projects on frequency and time dissemination (NEAT-FT and ITOC) and the frequency comb research undertaken at NPL as combs are a crucial part of the principle of the two-carrier transfer technique.

Risks
The full implementation and test of the two-carrier technique requires that an optical link is available from NPL to an other locations (such as the University of Southampton). Such link is being procured, but it has not been secured yet at present.
Because the two-carrier transfer concept has never been demonstrated before, there are intrinsic risks as always as an innovative idea is investigated. However, preliminary tests conducted so far give confidence that the technique has good potential to work in its full implementation and the great advantages the technique could lead to over other existing techniques (and the leading position NPL would gain from this work) make it worthwhile investing resources into it.

Knowledge Transfer and Exploitation
The outputs of the project will be disseminated primarily by publications in peer-reviewed journals, presentations at leading international conferences and workshops in the time and frequency area. The potential for developing the intellectual property will be investigated jointly with the collaborators, system providers and new end-users of high precision distributed time and frequency systems

Co-funding and Collaborators
This work will be in collaboration with the University of Southampton and the University of St. Andrews

Deliverables

1	**Start: 01/01/2013**	**End: 31/12/2013**	**Cost:**

Deliverable title: Two-carrier transfer technique basic principle tested
Basic principle tested on a 25 km fibre spool. Transfer stability and accuracy measurement.

2	**Start: 1/1/2014**	**End: 31/12/2014**	**Cost:**

Deliverable title: Two-carrier transfer technique demonstrated over 100 km of fibre
Full implementation of the transfer technique using one or more ultra-stable lasers and comb technology. Transfer stability and accuracy measurement.

3	**Start: 1/1/2015**	**End: 31/12/2015**	**Cost:**

Deliverable title: Two-carrier transfer technique demonstrated over 1000 km of fibre
Full implementation of the transfer technique on links (spooled or installed) approaching 1000 km. Transfer stability and accuracy measurement.

4	**Start: 1/06/2013**	**End: 31/12/2013**	**Cost:**

Deliverable title: Engineering of the cavity control electronics
The two-carrier technique will require two ultra-stable cavity-stabilised lasers operating in the optical communications band, with one of them located in the remote laboratory (for example the University of Southampton), in order to test the technique over an installed fibre. This transportable stabilised laser does exist, but its electronics needs to be engineered to be more robust and remotely controllable.

Project No.	EMT 13007	Price to NMO	£741k
Project Title	**Universal Synthesizer Based on an Optically Referenced Femtosecond Comb**	Co-funding target	
Project Lead	Helen Margolis	Start Date	01/01/2013
Project Team	Luke Johnson, Giuseppe Marra, Geoff Barwood, Steven King, Maurice Lessing (EngD student), Patrick Gill	End Date	31/12/2015

Summary This project will demonstrate a continuously operating universal frequency synthesizer based on an optically referenced femtosecond comb that could provide a single reference source to replace a number of wavelength-specific individual local oscillators. Referenced to a state-of-the-art ultrastable laser system, this will provide both high stability optical signals suitable for probing optical atomic clocks and high stability microwave signals suitable for use as local oscillators for microwave atomic fountains. It will also be used to transfer the stability of the optical atomic clocks to the 1.5 µm region for remote frequency comparisons using optical fibre networks.

The Need

Current optical clock lasers at NPL have fractional frequency stabilities of around 10^{-15} for averaging times of 1 – 10 s. This is limited mainly by thermal noise in mirror substrates and coatings that causes fluctuations in the length of the ultra-low-expansion cavities used to stabilize the lasers. Their performance imposes a technical limit to the short-term stability that could otherwise be achieved for the Sr^+ and Yb^+ (octupole) optical clocks and the strontium lattice clock. Improved clock lasers are therefore required for these three systems, as well as for the proposed Al^+ optical clock.

Cavities with lower thermal noise floors can be constructed by using different mirror substrate materials, longer cavities, cavity modes with larger areas, or cavities at cryogenic temperatures. NIST have recently demonstrated a room-temperature cavity with a thermal noise floor of $2–3\times10^{-16}$ for averaging times from 1–10 s, whilst PTB have demonstrated a cryogenic silicon cavity that achieves a short-term stability of 1×10^{-16} for averaging times of 0.1–1 s. Completely different approaches such as superradiant laser sources or the use of spectral hole burning for laser stabilization are also being investigated at NIST and JILA, but do not yet match state-of-the-art performance.

The short-term stability of the NPL caesium fountain primary frequency standard is also limited by its local oscillator; although it has a systematic fractional frequency uncertainty of just 2.3×10^{-16}, an averaging time of 20–30 days is required to reach a comparable statistical uncertainty. The SYRTE fountains, which use a cryogenic sapphire local oscillator, have demonstrated a short-term stability that is limited by quantum projection noise to $1.6\times10^{-14}\,\tau^{-1/2}$. An improvement in the local oscillator for the NPL caesium fountain could therefore result in significant improvements in the averaging times required to achieve a given accuracy. This would benefit both the stability of UTC(NPL) and the averaging times required for absolute frequency measurements of optical clock transitions.

Finally, it is necessary to be able to transfer the frequency stability of the optical clocks to an oscillator in the 1.5 µm region of the spectrum to support comparisons between optical clocks in different NMIs using optical fibre networks.

The Solution

Rather than develop separate state-of-the-art local oscillators for each individual optical clock plus the caesium fountain, we propose to develop a single system that is capable of meeting all these needs simultaneously. This will be based on a dedicated femtosecond optical frequency comb that is referenced to a single state-of-the-art optical local oscillator. The comb acts to transfer the stability of the initial optical reference not only to other optical frequencies (different comb modes) for the optical clocks and frequency transfer experiments but also to the microwave region of the spectrum (comb mode spacing) for use with the caesium fountain. This approach builds on research activities undertaken in previous NMS projects (stable lasers, femtosecond combs, frequency transfer over fibre networks).

Project Description

The initial master oscillator for the universal synthesizer will be based on a room-temperature cavity designed to have a state-of-the-art thermal noise floor. This will be developed and characterized during the first year of the project. In parallel we will review the possible options for a next-generation master oscillator and make recommendations for development work to be carried out in years 2 and 3 of the project.

A new femtosecond comb system will be specified and purchased to provide the means to transfer the stability of the master oscillator to other spectral regions. This is likely to be based on mode-locked fibre laser technology, but the

relative merits of Yb-doped and Er-doped fibre lasers will be carefully assessed before a final selection is made. In parallel, work will be carried out with our existing femtosecond combs to improve the stability of our optical frequency ratio measurement systems. This requires improvements in the signal-to-noise of the beats between the clock lasers and the comb, for which techniques such as injection locking or repetition rate multiplication will be explored. Once the dedicated comb is available, we will use these improved measurement systems to demonstrate transfer of frequency stability from the master oscillator to each of the clock lasers at NPL, as well as a 1.5 µm laser for optical frequency transfer over fibre networks. The performance will be verified by optical frequency ratio measurements using our existing femtosecond combs. An improved microwave local oscillator for the NPL caesium fountain will be generated, based on detection of the optical pulse train from the femtosecond comb. Finally, work will be carried out to develop systems for remote monitoring and control of the universal synthesizer, as well as automatic re-locking systems, to ensure that the complete system is capable of operating continuously and autonomously for extended periods. Also included in this project is the necessary femtosecond comb work to support the absolute frequency measurements and optical frequency ratio measurements to be carried out within other projects.			
Impact and Benefits The proposed solution has the benefit that any improvements in either the master optical oscillator or the femtosecond comb will lead to immediate improvements in the local oscillators available for all the optical and microwave frequency standards. It is a much more innovative and cost-effective approach than improving each local oscillator individually.			
Support for Programme Challenge, Roadmaps, Government Strategies This project is strongly aligned to the time and frequency roadmaps for the EMT programme which deliver the NMS strategy key objectives to provide time and frequency traceability in an optimized way.			
Synergies with other projects / programmes This work has strong synergies with the projects to develop optical atomic clocks based on single trapped ions and neutral atoms, and the project on primary frequency standards, since it will enable improvements in local oscillators to be implemented on all these systems simultaneously in an efficient and cost-effective way. It also supports the project on frequency transfer via optical fibre.			
Risks Delivery of this project will be dependent on timely procurement and delivery of a significant capital purchase: a dedicated femtosecond optical frequency comb, and the availability of a suitably quiet laboratory space.			
Knowledge Transfer and Exploitation The outputs of the project will be disseminated primarily by publications in peer-reviewed journals and presentations at leading international conferences.			
Co-funding and Collaborators This work will be undertaken in collaboration with the University of St Andrews, with a jointly supervised EngD student participating in the project.			
Deliverables			
1	**Start: 01/01/2013**	**End: 31/12/2013**	**Cost:**
Specification, recommendations,procurement and initial tests of universal synthesiser			
2	**Start: 01/04/2013**	**End: 31/12/2015**	**Cost:**
Improvements to stability of optical frequency ratio measurement systems			
3	**Start: 01/04/2013**	**End: 31/12/2015**	**Cost:**
Absolute frequency measurements and optical frequency ratio measurements of optical frequency standards			
4	**Start: 01/01/2014**	**End: 31/12/2015**	**Cost:**
Transfer of stability from master oscillator to other optical wavelengths Year 2: demonstration with selected clock laser and verification of performance Year 3: extension to other clock lasers and 1.5 µm laser for frequency transfer over optical fibre			
5	**Start: 01/01/2014**	**End: 31/12/2014**	**Cost:**
Improved microwave local oscillator for the Cs fountain primary frequency standard			
6	**Start: 01/01/2014**	**End: 31/12/2015**	**Cost:**
Development of next-generation optical master oscillator			
7	**Start: 01/01/2015**	**End: 31/12/2015**	**Cost:**
Continuous operation of the complete universal synthesizer for periods exceeding 10 days			

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Technical Theme

Contract and Programme Managment

Project No.	EMT13029	Price to NMO	244.5k
Project Title	**Contract Management and strategic representation of programme**	Co-funding target	N/A
Lead Scientist	Rhys Lewis	Stage Start Date	01/01/2013
Scientist Team	n/a	Stage End Date	31/12/2103

Summary

This project will deliver effective contract management for the programme. Work in this project will ensure timely invoicing and reporting to the NMO each month and delivery of an annual progress report to the NMO and programme working group.

The Need

Contract management is essential to ensure seamless delivery of the science projects in the programme while attending to all reporting and invoicing requirements of the NMO. A central point of control is also required for effective operational oversight and governance of the programme.

The Solution

This project will deliver effective contract management through a contract manager dedicated to this programme. They will have oversight of all:

- Project delivery;
- Invoicing;
- Contract status and variations;
- Monthly and annual reporting.

Project Description (including summary of technical work)

1. Attend meetings as necessary to support contract delivery and the needs of the NMO
2. Prepare reports monthly (invoices, progress report and financial forecasts)
3. Liaison with working group, industrial advisory groups & clubs
4. Manage delivery of the contract and submit change requests and contract amendments as necessary
5. Analysis of programme performance and revenue forecasts for the financial year
6. Ensure that the contract is managed to NPL's ISO 9001 accredited quality system
7. Deliver annual report and present programme progress to working group and the NMO as required.

Impact and Benefits

This project will ensure that all operational, financial and reporting requirements for the programme are met. The work in the programme covers the oversight of delivery from all the technical projects and hence is where ultimate responsibility lies for the success of the programme.

Support for Programme Challenge, Roadmaps, Government Strategies

Not applicable.

Synergies with other projects / programmes

Not applicable.

Risks			
The main risks are the inability to deliver the monthly reports and invoices to the NMO and the failure to deliver the annual report to the programme working group. Both of these risks are mitigated by the availability of a large pool of senior managers who are available to step in to assist or take over delivery if adverse circumstances are causing problems with the completion of the key tasks of this project.			
Knowledge Transfer and Exploitation Not applicable.			
Co-funding and Collaborators Not applicable.			
Deliverables			
1	**Start: Jan 2013**	**End: Dec 2013**	**Cost**
Effective management of the NMS Physical Metrology Programme to deliver maximum benefit to the UK economy and quality of life.			
2	**Start: Jan 2013**	**End: Dec 2013**	**Cost**
Strategic representation of the programme			

Project No.	EMT 13030	Price to NMO	181k
Project Title	**Programme Management and Formulation**	**Co-funding target**	N/A
Lead Scientist	Bill Nimmo	**Stage Start Date**	01/01/2013
Scientist Team	n/a	**Stage End Date**	31/12/2103

Summary

This project will formulate a proposal of work for inclusion in the 2012/15 programme and engage with key stakeholders to ensure maximum impact is achieved from the science delivered by the programme. To achieve these objectives the project will:

- Maintain and develop the programme strategy and roadmaps;
- Consult with key stakeholders in government, industry, academia, regulators and other end users in order to determine future measurement requirements or other related issues that need to be addressed by the programme;
- Develop a series of project proposals for prioritisation by the programme working group;
- Implement and maintain a balanced scorecard for the programme as a measure of the impact of the programme on the UK economy and society.

The Need

New measurement requirements are constantly emerging from all areas of UK life. For example, new technologies require new underpinning metrology and standards, as do new regulations or environmental targets. To underpin areas such as growth in the economy, public health issues or mitigation of environmental impacts these measurement requirements must be successfully addressed as early as possible. In order to achieve these objectives effectively an overview of the research priorities and how to address them is required. Maintaining and developing a programme strategy and roadmaps achieve this objective and allow, in conjunction with knowledge of specific technical requirements obtained through stakeholder consultation, the formulation of a work programme that address UK measurement needs. Both the careful design of any programme of work coupled with the continual review of opportunities for increased impact are essential in order to make sure that the maximum value possible is extracted from the investment made in the technical projects.

The Solution

The views of a wide range of stakeholders from industry, regulators, government and other end users will be sort through a wide ranging consultation process in order to capture current and emerging measurement requirements. This process will include looking at independent evidence of measurement needs as expressed in government reports, foresight activities, industry roadmaps etc. as well as conducting meetings, surveys and interviews as required that focus on specific topics of interest. Collation and assessment of information from all sources will enable the programme strategy and roadmap to be developed which will guide the future direction of the programme. The detailed technical requirements will then formulated into a series of projects for prioritisation by the independent programme working group. Projects that receive the highest ranking will form a programme of work, which will be initiated at the start of the next programme cycle.

In addition to the programme formulation, work will be undertaken to understand and maximise the impact of the research. This will be assisted by the implementation and maintenance of a balanced scorecard for the programme consisting of a number of key metrics. The balanced scorecard will be developed initially as part of the Pan-Programme KT activity.

Project Description (including summary of technical work)

- Horizon scanning, capture and analysis of Industry and Societal needs to feed into current and future programme direction;
- Development and updating of programme roadmaps and strategy;
- Engagement with programme stakeholders to:
  - Realise outputs and maximise benefits to the UK;
  - Ensure alignment of programme with UK Government, Industry and Societal drivers;
- Oversee preparation of project proposals for review and prioritisation by the programme working group;
- Submission of final programme proposal for contracting;
- Liaison with the NMO programme supervisor to deliver maximum impact and efficient delivery;
- Identification of exploitable material for increased impact through channels provided by the Pan-Programme KT programme and other KT avenues;
- Assessment of the impact of the programme through use of a balanced scorecard;

Impact and Benefits

Effective programme management will maximise the outcomes to key stakeholder communities from the outset of the technical work and ensure knowledge transfer activities in the programme are efficient and effective. The programme as a whole addresses many measurement challenges across the broad sweep of the UK economy and society. Therefore, the design of knowledge flows and exploitation plans in technical projects which occurs during the formulation process is essential for delivery of the wide benefits of the programme to the broadest possible audience.

Support for Programme Challenge, Roadmaps, Government Strategies

This project underpins the work of the whole programme through development of an overview of key societal drivers and measurement requirements as captured in the programme strategy and roadmaps. These key programme documents are utilised during development of technical projects to guarantee that all the technical work in the programme is aligned to addressing the metrology needs of the UK.

Synergies with other projects / programmes

This project will interact with the other NMS programmes so that synergies and common goals can be identified to ensure that the maximum value is returned from the investment in the NMS portfolio.

Risks

This project has no technical risks but is dependent on the availability of senior staff to assess and interpret the societal drivers in order to develop the programme strategy and roadmaps and hence determine the future technical work required in the programme.

Knowledge Transfer and Exploitation

The main functions of this project are to ensure the development of a new programme of work and to measure and increase the impact of the programme. Improvement of the programme impact will be achieved through proactive intervention in the technical projects within the programme rather than through direct knowledge transfer activity in this project.

Co-funding and Collaborators

Not applicable.

Deliverables

1	**Start: Jan 2013**	**End: Dec-2013**	
Continuous consultation with industry and on-going programme formulation			

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