NATIONAL MEASUREMENT SYSTEM

PROGRAMME FOR

ELECTROMAGNETIC METROLOGY

October 2003 to September 2006

PROGRAMME OUTLINE

SEPTEMBER 2003

CONTENTS

Overview of the Document

This document outlines the proposed content of 2003-2006 NMS Electromagnetic Metrology Programme in the form of requirements that have been interpreted from the consultation process; the objectives and deliverables that will address these requirements; and the benefits that will accrue. The programme content is significantly more than is likely to be resourced and so the deliverables need to be prioritised. The aim of the document is to facilitate the process of identifying the highest priorities for the Programme so that a detailed work programme can be constructed to enable the most important deliverables to be achieved.

The document contains:-

Section 1: An introduction to the Electromagnetic Programme's role and objectives within the National Measurement System.

Section 2: A description of the main formulation process.

Section 3: An overview of the Theme Structure of the proposed programme.

Sections 4: Summary of each Theme.

Project descriptions are given in a separate volume.

The transfer of knowledge developed within the programme to the beneficiary communities is an essential part of every project; this will be achieved through seminars, publications and news articles. Only where there are proposed specific technical knowledge transfer activities, for example holding a workshop, training course or contributing to the deliberations of a standardisation committee, are these knowledge transfer deliverables detailed. At this stage there are no proposals on how the technical work should be delivered.

The Electromagnetic Programme is one of the largest NMS programmes covering a range of standards and technologies, and benefiting many disparate sectors of industry. The Theme structure has been chosen to group outputs addressing similar industry needs or technologies, or serving specific sectors of industry. The themed structure and links should enable the reader to identify the sections of the document of particular relevance to his or her interests.

1 Introduction to the Electromagnetic Programme

1.1 Background

The UK National Measurement System (NMS) is the national framework within which organisations such as the National Physical Laboratory establish primary standards of measurement (for mass, length, time, electrical quantities etc.) which are then rigorously linked to practical measurements in industry and commerce, local and national government, hospitals, research and the home by an unbroken chain of measurement comparisons all having stated uncertainties. In formal terms, it is the infrastructure ensuring that measurement in the UK is valid, fit for purpose, and internationally recognised.

The DTI National Measurement System Directorate (NMSD) is responsible for securing the objectives of the NMS, through programmes of work in which it acts as a customer on behalf of a wide range of ultimate beneficiaries in the UK, and through further development and interpretation of underlying Government Policy. NMSD's aim is to promote industrial competitiveness by providing a comprehensive National Measurement System for industry, and acting as the centre within Government for policy on measurement standards for industrial, commercial, environmental, healthcare and regulatory use.

The Electromagnetic Metrology Programme is one of several National Measurement System programmes whose purpose is to ensure an effective, competitive and comprehensive measurement infrastructure to:

- support productivity and facilitate innovation within UK industry
- meet statutory and regulatory obligations
- facilitate free trade

1.2 Role of Electromagnetic Measurement in the UK

The basis

Electrical and electromagnetic technologies pervade virtually every aspect of our lives, so much so that modern society is inconceivable without them. They facilitate wealth creation in both the industrial and service sectors, and are, perhaps, the most important factors in maintaining and extending our quality of life. Electronics, communications and Information Technology, three key sectors, are totally dependent on them.

The ability to measure electrical quantities in a consistent and repeatable manner is vital for maintaining and extending the economic and technical success of electrical and electronic technologies, from power generation and distribution to the development and exploitation of the most advanced communication systems.

A set of internationally recognised measurement standards for electrical quantities is at the heart of the system of electrical measurement. Although the *ampere*, the unit of measurement of electric current, is one of the base units of the International System (SI), it cannot be realised with sufficient accuracy to be the foundation of practical electrical measurement. Instead, the derived SI units of electrical potential, the *volt*, and of electrical resistance, the *ohm*, have become the bases for electrical measurement. Historically these have been determined from the base SI units via the 'moving coil experiment' and the calculable capacitor. Today the primary working standards of voltage and resistance are realised in terms of quantum phenomena and are defined, by international agreement, in terms of SI measurements of the Josephson and von Klitzing constants respectively.

Industrially, voltage and resistance measurements extend over many decades, for example, from microvolts or less in electronic systems to millions of volts in electrical power systems, and from microohms in power circuits to teraohms in high voltage, low current applications. However, in many applications, the measurement of resistance or voltage is an intermediate step in the measurement of other physical quantities since most sensors work by converting physical changes to changes in resistance or voltage (or, in some instances, capacitance). One of the most demanding resistance measurement applications is in the measurement of temperature via the platinum resistance thermometer.

However, electrical measurement standards not only have to underpin measurement over many orders of magnitude of each quantity but also have to cover the frequency dimension, where the technologies, the measurement medium and even the concept of the physical quantity change significantly in the transition from low to high frequencies. Microwave measurements are necessarily made in distributed systems where the dimensions of the equipment may be many wavelengths. Signals are propagated along and guided by transmission lines between elements of the circuit. Voltages and currents on transmission lines are oscillatory in nature and have a period and associated wavelength which are determined by the frequency and phase velocity of the line. The relationship between voltage and current can, in its simplest form, be expressed as the characteristic impedance of the transmission line. The notion of voltage or current is not, however, very useful. Irregularities in the propagating medium, and discontinuities at connections and junctions set up standing waves such that voltage measurement becomes arbitrary. The concept of time-averaged power flow through a microwave circuit is, however, meaningful and forms the basis of measurements at microwave frequencies.

The context

The industrial needs for electromagnetic measurements are very diverse, and this is reflected in the range of capabilities required at the national standard level. Applications supported range from the relatively mature to the most novel and fast moving, in many of which the UK has a leading edge either as a manufacturer or in exploiting the wider benefits of use. The main factors in setting the objectives and deliverables for the programmes are:-

Affects on key sectors

The sectors primarily affected such as electronics, telecommunications, information processing, defence, broadcasting, energy, transport and various aspects of health are widely recognised (for example in 'Foresight' studies) as those that will shape our changing technical and social environment. They are also the sectors that will dominate the economic well-being and competitiveness of the UK.

Leading edge requirements

For many industrial activities, availability of the best measurement capability is paramount for competitiveness. Most obvious here is the instrumentation sector, but for example, mobile telecoms, satellite communications and high data-rate processing all demand leading-edge metrological capabilities. The UK has a proven culture of innovation and has a firm presence in the supply of leading-edge equipment and systems based on electronic, and RF and microwave technologies.

Regulatory drivers
Regulatory requirements, such as for electromagnetic compatibility, the quality of electrical supply parameters, electricity metering, and health and safety are all strong drivers for measurement traceability. Although the European Commission and national governments are seeking to reduce the burden on industry of conforming to Directives through their rationalisation and simplification, a key element in reducing the burden is the provision of reliable and cost effective measurement techniques.

International standardisation
The globalisation of markets puts particular emphasis on international specification standards and the need for ensuring the integrity of metrology and accreditation world-wide. Standardisation in the electrotechnical sector is forecast by CENELEC to become more and more complex as a result of the integration of electrotechnology, in particular electronics, into systems which are used across several sectors of industry, and as a result of the further shortening of periods for innovation and life cycles of products.

It is important that specification standards are supported by reproducible test methods and underpinned by robust measurement standards. Therefore, the NMS Electromagnetic Programme must take into account the needs of international standardisation and support the deliberations of the standardisation committees either directly or through the established network of national delegates.

It is also essential that the UK's primary measurement standards are harmonised with those of the UK's trading partners. There are regional groupings of national measurement institutes, such as EUROMET (in Europe), NORAMET (in North America) and APAM (Asia-Pacific), which organise within their boundaries structured intercomparisons of national measurement standards. At the global level, the Comité International des Poids et Mesures (CIPM) and its various consultative committees organise 'key comparisons' between representative NMIs in these regional groupings. The process of intercomparison has been formalised through the signing of a Mutual Recognition Arrangement under which the results of intercomparisons are used to establish the 'equivalence' of national measurement standards. An important element of the NMS Electromagnetic Programme is therefore devoted to international activities aimed at demonstrating the international equivalence of UK electrical and electromagnetic standards through EUROMET and CIPM intercomparisons.

Small to Medium Enterprises (SMEs)
There is an increasing role served by SMEs in the electronics, instrumentation and telecommunications sectors where they have the flexibility to satisfy demand for customisation. It is important that SMEs have access to measurement standards, and affordable and internationally accepted measurement techniques to demonstrate conformance of their products to international specifications.

Traceability to support accreditation
The network of UKAS accredited laboratories for electromagnetic measurements is well established, particularly in the DC and LF and guided wave fields. It is estimated that these laboratories issue over 100,000+ UKAS certificates each year. These laboratories depend on traceability to national measurement standards.

Skills and best practice in metrology

The skills to support the burgeoning metrological demands of accredited measurement and test, quality system certifications and leading edge technical developments in the UK are specialised. Enhancing and making more efficient use of these skills in the UK remains of great importance.

1.3 Objectives and Scope of the Programme

The NMS Electromagnetic Metrology Programme covers the realisation, maintenance and development of measurement standards for electrical, magnetic and electromagnetic quantities used in the frequency range DC to near optical frequencies. These quantities include DC voltage, AC voltage and AC/DC transfer, AC voltage ratio, AC and DC resistance, capacitance, inductance, AC power, AC conductivity and magnetic standards at frequencies below about 10 MHz. RF and microwave quantities, which are typically but not exclusively above this frequency, include power, attenuation, impedance, noise, electric field strength, power flux density and antenna parameters. Standards for laser power (above 10 mW) and energy have traditionally been associated with the Electromagnetic Programme. The programme also encompasses the development of standardised methods of measurement for the above quantities to meet UK needs.

The objectives of the programme are:

- to maintain and develop national measurement standards for DC and Low Frequency electrical and electromagnetic quantities, including the derived SI units of the volt and the ohm, and RF and Microwave electromagnetic quantities at a level consistent with the current and future needs of UK industry, national and local government, and research, and make them accessible to customers in as practical and economic form possible.

- to ensure that the UK measurement standards for electromagnetic quantities are harmonised with those of the UK's trading partners, through intercomparisons and collaborative research leading to mutual recognition.

- to develop new and improved methods of measurement for electromagnetic quantities to meet identified UK needs, and promote international standardisation of these methods to ensure consistency in practical measurements, especially where these are used for regulatory and trading purposes.

- to promote knowledge transfer from the programme and the adoption of good measurement practice, and to provide technical support and advice to UK organisations and individuals undertaking measurement of electromagnetic quantities.

These objectives reflect the fact that accurate measurements, or more precisely measurements of well-defined (and low) uncertainty, require three essential elements.

- a traceably-calibrated measuring instrument, that is one whose calibration is linked by an unbroken chain of comparisons to a primary standard of measurement,

- an agreed method of measurement, preferably standardised nationally or internationally by an appropriate standardisation body (BSI, CENELEC, ISO, IEC),
- a trained and informed measurement practitioner.

It is the need to support these fundamentals of reliable and reproducible measurement that defines the scope of the programme.

2 Method of formulation

The development of a new programme goes through three phases: orientation, formulation and prioritisation. The orientation phase of this development was undertaken by PA Technology and completed in September 2002. The orientation process identified major economic, technology, regulatory and social drivers that helped define the scope of the new programme.

NPL has been contracted to formulate the 2003 – 2006 NMS Electromagnetic Metrology Programme on behalf of the National Measurement System Directorate. This document is the principle deliverable of the formulation phase of programme development.

NPL's extensive links with end users of the entire range of electromagnetic standards in UK industry and commerce, national and local government, and academia, and contacts with the wider international metrology community, have been used to obtain information on requirements from which the proposed programme has been formulated. Sources have included:

- customers and potential customers for measurement services maintained and developed within the current Electromagnetic Programme (through meetings and site visits),
- statistics on demand for measurement services maintained and developed within the current Electromagnetic Programme, and relevant trends in UKAS-accredited laboratory services,
- participants at NMS Club meetings and Workshops,
- instrument manufacturers and representatives from organisations in the major industrial sectors supported by the Electromagnetic Programme,
- professional bodies and trade associations,
- policy statements and work programmes of international organisations (CENELEC, EA, ISO, IEC) concerned with specification standards and measurement protocols,
- discussions concerning future international measurement intercomparisons for electromagnetic quantities organised under the auspices of the CIPM and EUROMET, and
- discussions with other NMS programme managers, where electrical quantities underpin other quantities and where there is synergism with other programmes, for example the NMS Knowledge Transfer Programme.

Comments received on this 'Draft for Comment' will help refine the content of the programme which will then go forward for prioritisation and appraisal by the DTI's National Measurement System Policy Unit and the Measurement Advisory Committee Working Group of experts.

3 Structure of the programme

The current NMS Electromagnetic Programme encompasses both DC and LF, and RF and microwave metrology. Recognising that DC and LF, and RF and Microwave quantities continue to underpin the whole of electromagnetic metrology and are largely disseminated via a well-established network of UKAS accredited calibration laboratories, the maintenance and development of these quantities are described within the **DC and LF Theme** and **RF and Microwave Theme** in the proposed programme.

Many derived quantities, however, support groupings of industrial sectors or address specific regulation or technologies. Hence other Themes have been introduced into the proposed programme to best represent them, specifically:-

Antenna Measurement Theme
This Theme covers the calibration and characterisation of a broad range of antenna types from 100Hz to 100GHz using the National Open Area Test Site (OATS), extrapolation range, spherical scanner and Fully Anechoic Room (FAR). Antenna calibration underpins electromagnetic field measurement and EMC as well as supporting the telecommunications, aerospace, defence and other sectors.

Electromagnetic Field Measurement and Mapping
The Theme encompasses the measurement of electromagnetic fields both in free space and in liquids (specifically tissue equivalent materials) and is aimed particularly at the calibration of Power Flux Density (PFD) probes and probes to measure Specific Absorption Rate (SAR) respectively. A major use for these probes, for which confidence in measurement is essential, is to measure electromagnetic fields to which workers and the general public may be exposed. The development of new probe types, including non-invasive electro-optic probes, is included in this Theme.

Electromagnetic Compatibility Theme
Virtually all electrical and electronic equipment manufactured and sold within the European Community must comply with the Electromagnetic Compatibility Directive to ensure that they operate reliably in a given radiated field strength and that they will not radiate more than a specified level so that they will not render other equipment unreliable. The Directive has recently been complemented by regulations setting a limit on the level of harmonics generated by appliances and equipment connected to the mains. This Theme provides measurement standards to give confidence in measurements made to demonstrate conformance to these regulations as well as investigating cost effective measurement techniques.

Waveform Theme
This Theme addresses the measurement of fast pulses and parameters in the presence of complex waveforms. Major drivers for this Theme are the increasing sophistication of digital electronic equipment operating to higher frequencies and of communication systems using complex modulation techniques to maximise the use of the electromagnetic spectrum.

Electromagnetic Materials Theme
Magnetic and dielectric materials are central to many electrical and electronic components, from the cores of transformers to electrically tuneable narrow band filters used in mobile communication systems. The characterisation of these materials is important to support

manufacturing processes and facilitate innovation in the development and exploitation of new types of materials. This Theme underpins the traceable measurement of the electromagnetic properties of materials through the provision of reference standards and measurement facilities. The work within this Theme is complementary to the work undertaken within the NMS Programme on Materials Metrology.

Laser Power and Energy Theme

Laser Power (above 10mW) and Energy has been historically linked within the Electromagnetic Programme and is currently a Theme within the RF and Microwave area. However, there is increasing synergy between this Theme and the measurement of power in optical communications systems as the power density in optical fibres increases. Although projects are presented here for comment, it is recommended that this Theme should transfer to the 2004 – 2007 NMS Photonics Programme in April 2004.

Future Technologies Theme

The Programme needs to investigate relevant emerging technologies so that it can 1) exploit these technologies for realising improved standards for electromagnetic quantities, 2) provide metrological expertise to help industry exploit these technologies, and 3) to position the NMS to provide future measurement standards required in their main-stream manufacturing.

Such technologies identified in the Orientation Report and included in this Theme are electronic devices fabricated with nanometre dimensions, micro machined devices (MEMS) and those technologies supporting applications in the Terahertz region of the electromagnetic spectrum.

Knowledge Transfer Theme

This Theme covers overarching knowledge transfer activities, including the running of NMS Clubs, UK representation on BIPM Consultative Committee for Electricity and Magnetism and the EUROMET Electricity Experts Group, partnering with professional organisations to maximise the output of the programme. Organising the biannual British Electromagnetic Conference and the 2004 Conference on Precision Electromagnetic Measurement is also included.

Programme Management Theme

This Theme provides management of the delivery of the programme and ensures that the objectives are met within time and budget. It also assists the DTI in formulation of the follow-on programme.

4.1 Theme 1: Direct Current and Low Frequency Electrical Standards

This Theme supports the realisation and dissemination of standards for Direct Current and Low Frequency quantities, specifically voltage, resistance, AC/DC transfer, AC voltage, AC power, capacitance, inductance, AC voltage ratio and current transformers. Also included in this Theme are developments in specific areas to meet evolving industry needs for lower uncertainties and/or increased range of measurement, as well as activities to replace ageing facilities and software.

The comparison of DC and LF standards maintained by the UK NMS with those of the measurement systems of our trading partners is essential to demonstrate equivalence of units as well as give confidence in the realisation of standards. Such international comparisons are co-ordinated under the auspices of the BIPM and EUROMET and are implicit within this theme. The transfer of technical knowledge to industry is also implicit within each project.

The principle route for dissemination of DC and LF electrical quantities is through an established network of over 90 UKAS accredited calibration laboratories in the electrical area with others taking traceability for electrical quantities in order to provide calibration services in other fields, for example temperature measurement. The number of UKAS calibration certificates in the electrical area (including RF and microwave) is estimated to exceed 100,000+ per annum. The UK NMS also provides underpinning traceability for parts of the measurement infrastructure in other countries that do not have their own primary standards.

Virtually all areas of the economy are affected by electrical measurement, however the greatest impact is in the manufacturing sector, particularly the manufacture of electrical and electronic goods. Electrical standards are also essential for the metering of electricity. Indeed all aspects of our daily lives are dependent on electrical measurement - in the home, at leisure, in transport, in education and through health, emergency and security services - the list is endless.

Reliable measurement techniques supported by accurate measurement standards and the infrastructure needed to disseminate these standards to the end user are vital to underpin the development and exploitation of electrical and electronic technologies and the vast range of manufacturing and service sector activities dependent on them. Electrical measurement standards are needed just as much to meter the electrical supply to the domestic consumer as to measure an electronic component in an advanced communication system.

Background

Although the ampere is the base SI unit and as such is used to express derived electrical units, it is the realisation of the volt and the ohm which underpin the metrology of electrical quantities. Physical effects based on quantum phenomena are now used to establish reference standards for voltage and resistance through the Josephson effect and quantum Hall effect respectively. Other parameters such as capacitance, inductance and power are derived from realisations of the volt and ohm.

Investments made in previous Electromagnetic Programmes has provided the UK with some of the most comprehensive facilities of any NMS for the realisation and dissemination of DC and LF standards with uncertainties well suited to industry needs. Hence no fundamental developments are proposed in the realisation of basic electrical quantities during the 2003 - 2006 programme.

AC quantities are still derived from DC quantities using AC/DC thermal converters transfer in which the heating effects of applied AC and DC signals are compared by means of one or more thermoelectric junctions; these techniques limit the accuracy with which AC quantities are realised. A project to generate AC voltages with the quantum accuracy of DC voltage is the subject of a project within the Future Technologies Theme whilst another is aimed at exploiting the metrological potential of manipulating and counting single electrons. Such projects will provide a basis for enhancing the integrity and accuracy of electrical units to meet industry's demands for lower uncertainties in the future.

Trends

In common with all base and derived SI units, the uncertainty with which the volt and ohm have been realised has gradually fallen with time. Drivers for this have come from the instrumentation sector where accurate measurement standards are required to turn improvements in instrument reproducibility into meaningful accuracy. Instrument developments have, in turn, been driven by manufacturing industry's needs to make more accurate measurements of electrical quantities or of other physical parameters, which are converted to electrical quantities via a transducer, as manufacturing complexity has increased and manufacturing tolerances decreased.

Advances in digital electronics and in processing speed have pushed the requirements to make electrical measurements to higher frequencies. Projects to meet these needs have been provided in the current Electromagnetic Programme and the commissioning of an impedance measurement capability to 10MHz is included in this programme.

Electrical standards are essential for metering the supply of electricity at all stages in its generation, distribution and use. The opening up of the electricity market following privatisation has created more demand for metering whilst the growing harmonic content of the supply due to non-linear loads is causing specific problems for accurate metering.

Justification

Economic

DC and LF standards are essential to underpin the traceability provided by over 90 UKAS accredited and other calibration laboratories for electrical and other quantities. The fan-out below these calibration laboratories is many thousand fold, supporting measurements in many industrial sectors, including electrical and electronic engineering, instrumentation and defence.

The turnover of UK based manufacturing industry in the sectors covering the manufacture of electrical equipment, electrical machinery and communication equipment was £47.5B in 2001, and the sector covering the manufacture of measuring and test instrumentation was £7.1B; together these sectors employ over 440,000 workers. The success of these sectors is heavily dependent on electrical measurement; particularly DC and LF measurements, to underpin manufacturing processes, ensure product quality and demonstrate that products conform to specifications or regulations.

Regulation
In 2001 321 terawatt hours of electricity were generated with an estimated value of over £15B. Accurate metering is essential to enable the market to function effectively and give confidence to the consumer, both industrial and domestic.

How projects have been chosen
The scope of activities to realise and maintain DC and LF electrical quantities has been based on current demands for calibration services, the views of UKAS accredited laboratories on future need, trends in instrumentation through dialogues with instrument manufacturers, and economic and technical trends within published reports. Such information has also been used to identify areas for development whilst risk assessments on the robustness of existing capabilities have enabled areas requiring refurbishment to be prioritised.

Summary of projects

1.1 Realisation and dissemination of DC and AC standards at frequencies up to 1 MHz
The project covers the realisation and dissemination of standards for Direct Current and Low Frequency quantities, specifically voltage, resistance, AC/DC transfer, AC voltage, AC power, capacitance, inductance, AC voltage ratio and current transformers, power analysers for harmonics and flicker, and magnetic field strength. International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

1.2 Development of DC and AC standards at frequencies up to 10MHz
The project covers incremental improvements to DC and AC standards, specifically increasing accredited capacitance measurements to 10MHz and improving access to voltage and resistance standards via provision of a remote calibration services. Internal maintenance activities include the replacement of sampling heads for power measurement, further automation of facilities to improve service provision and replacement of obsolete software. The development of new sampling heads would establish the basis for providing calibration capabilities for three-phase power should they be required in future.

1.3 Development of a calibration service for power measurement under non-sinusoidal conditions
The objective of this project is to develop a measurement system for mains frequency non-sinusoidal power leading to a calibration service with a target uncertainty of 75 ppm.

4.2 Theme 2: Radio Frequency and Microwave Electromagnetic Standards

This theme supports the realisation and dissemination of standards for the RF and Microwave Guided Wave quantities of attenuation, impedance, power and noise from a few kHz to 100GHz. Also included in this theme are developments in specific areas, particularly impedance measurement, to meet evolving industry needs for lower uncertainties and/or increased range of measurement, as well as activities to replace ageing facilities and software.

The comparison of guided wave standards maintained by the UK NMS with those of the measurement systems of our trading partners is essential to demonstrate equivalence of units as well as give confidence in the realisation of standards. Such international comparisons are co-ordinated under the auspices of the BIPM and EUROMET and are implicit within this theme. The transfer of technical knowledge to industry is also implicit within each project.

The principle route for dissemination of guided wave standards is through an established network of UKAS accredited and other calibration laboratories with a fan-out to industry of many tens of thousands of calibrations. The major sectors benefiting from these standards are telecommunications and defence, where the latter uses about 30% of the currently allocated electromagnetic spectrum. These are sectors exploiting RF and Microwave technologies where the UK has a long history of innovation and economic success.

Guided wave standards are also fundamental to all forms of measurement supporting RF and Microwave technologies and underpin antenna metrology (Theme 3), the measurement of electromagnetic fields for Health and Safety (Theme 4), EMC conformance testing (Theme 5) and waveform metrology (Theme 6).

Background
The principle quantities associated with measurements of RF and microwaves are power, attenuation, impedance and noise. There is a fundamental inter-relation between quantities for example, a measurement of power or attenuation is not meaningful without a statement of the impedance of the device under test in relation to that of the measuring standard, and a noise or power standard cannot be determined without a detailed assessment of the attenuation of the transmission line sections that thermally isolate the standard from the ambient surroundings.

The national standards for guided wave quantities at NPL are based on an extensive range of coaxial and waveguide systems. Investments made in previous NMS Electromagnetic Programmes have provided the UK with world leading capabilities for RF and microwave measurement in terms of the range of parameters covered and uncertainties offered. Such capabilities have contributed to the UK's leadership in RF and Microwave technologies, particularly in the telecommunications, defence and aerospace sectors.

Trends
Although the telecommunications sector has not sustained the rapid growth shown in the '90's, the medium term forecast predicts an annual growth of about 5% fuelled by the needs of customers for mobility, multimedia and broadband services. Over the next 10 years we can expect to see major new use of radio for communication services, with growth in digital broadcasting from satellite and terrestrial transmitters, mobile services offering video

communications, fixed network access in competition with local cable networks, and with wireless communications for the home and office. The overall result will be continued growth of capacity necessitating the opening up of new areas of the radio spectrum and planned re-use of capacity, currently used inefficiently, by new standards.

The re-use of the spectrum is evident in the 100 MHz to a few GHz region where bands formerly used for domestic or military services are being used for mobile communications. In addition, the high frequency end of the spectrum is being opened up by the development of new component technologies. The established use of the electromagnetic spectrum depends on the availability of existing measurement standards while new applications are putting pressure on the NMS for improved standards where frequencies are being re-used and new standards where new, higher frequencies are being opened up. The boundaries between microwave and photonic technologies will merge as the electromagnetic spectrum is used to even higher frequencies (see Project 9.6 in the Theme 9).

The commercial exploitation of microwave technologies is dependent on mass production of microwave circuits. There is an increasing integration of microwave components on gallium arsenide substrates to meet this commercial need.

Justification

Economic

RF and Microwave Guided Wave standards are essential to underpin the traceability provided by UKAS accredited and other calibration laboratories for these quantities. The fan-out below these calibration laboratories is many thousand fold, supporting measurements in the electronic engineering, telecommunications, instrumentation and defence sectors.

The UK market for telecommunications equipment, worth £5B, is served by a manufacturing sector that employs around 35,000 people and has a turnover of £6B. As a percentage of GDP, the sector makes a value added contribution of 0.3% and exports products worth over £4B worldwide. The success of this sector and others is heavily dependent on Guided Wave quantities to underpin manufacturing processes, ensure product quality and demonstrate that products conform to specifications or regulations. The telecoms manufacturing sector is dominated by inward investors and includes eight of the top ten global manufacturers. Market opportunities have also encouraged the emergence of a significant number of small innovative companies with niche products. A world leading measurement infrastructure for RF and microwave quantities in the UK is attractive to inward investors as well as supporting innovation in SMEs.

How projects have been chosen

The scope of activities to realise and maintain RF and Microwave Guided Wave quantities has been based on current demands for calibration services, the views of UKAS accredited laboratories on future need, trends in instrumentation through dialogues with instrument manufacturers, and a review of technical and economic trends within published reports.

The views of members of NMS Clubs, for example ANAMET, the Measurement Forum, and other professional groupings such as ARMMS have also been valuable in defining the projects. The information gathered has also been used to identify areas for development whilst risk assessments on the robustness of existing capabilities have enabled areas requiring refurbishment to be prioritised. Project 2.1 covers the provision of existing standards while Project 2.2 covers incremental development to meet the demand for lower uncertainties.

A significant element within this Theme is devoted to extending the accuracy and range of impedance standards and supporting impedance measurements within industry. This emphasis is driven by the importance of impedance measurement within industry, particularly the use of network analysers, and the developments in instrumentation. Projects 2.3 to 2.6 cover impedance measurement.

Project 2.7 has been selected to address the needs for improvements to on-wafer measurement techniques and accuracy.

Summary of projects

2.1 Realisation and dissemination of RF and Microwave standards

The project covers the realisation and dissemination of standards for RF and Microwave Guided Wave quantities, specifically impedance, power, attenuation and noise. International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

2.2 Development of RF and Microwave guided wave standards

Incremental developments aimed at reducing uncertainties and/or increasing the range of quantities measured are covered in this project; specific outputs include increased dynamic range of coaxial attenuation measurements systems, a power measurement system for 1.85mm connectors and reduced power uncertainties, and reduced uncertainties for noise calibrations. Developments to improve the accessibility of the standards include further development of the Internet enabled impedance metrology system and provision of on-line algorithms for characterisation of RF devices and parameter transformation.

2.3 Extend existing national impedance standard capabilities at microwave frequencies

The project is aimed at improving measurement uncertainties in the Primary Impedance Measurement Service through detailed air line standard modeling, and at developing new primary standard calibration services for coaxial open- and short-circuits and for multiport devices and some non-insertable devices.

2.4 New impedance standards for millimetre wave frequencies

It is recognized that there are limitations with existing technologies to provide impedance standards for millimeter wave applications. The project will undertake R&D into new forms of primary impedance standards based on dielectric waveguide technologies and also develop new calibration techniques appropriate to miniature coaxial connectors.

2.5 Measurement assurance techniques for industrial microwave impedance calibration facilities

The principle aim of this project is to investigate and provide guidance on techniques for establishing traceability for Vector Network Analysers at both low and high frequencies to complement the techniques given in European Accreditation Document 10/12: European Guidance Document on the accreditation of Vector Network Analysers.

2.6 Development of measurement techniques for calibration of high frequency impedance analysers

This project is aimed at developing techniques that extend present NMS capabilities for accurate impedance measurement to 100MHz. The work will be base on coaxial bridge techniques thus enabling accurate calibration of LCR meters.

2.7 International measurement reference for on-wafer calibrations

The objective of the project is to unify effort for advanced on-wafer measurement techniques and accuracy through developing structures, models and processes to enable techniques used within the coaxial bands to be applied to on-wafer calibration.

4.3 Theme 3: Antenna Calibration and Characterisation

This theme supports the calibration and characterisation of RF and microwave antennas from a few kHz to 100GHz. Also included in this theme are developments in specific areas to meet evolving industry needs for lower uncertainties and/or increased range of measurement. As with the previous themes, international comparisons are implicit within this theme as is the transfer of technical knowledge to industry.

Calibrated antennas are used to measure electromagnetic fields or generate fields of known magnitude and are therefore used in dosimetry (Theme 4) and in EMC conformance testing (Theme 5). They also provide traceability to UKAS and other calibration laboratories providing antenna calibration services and support industry needing to characterise antenna either during manufacture or in situ.

Antennas are an essential component in broadcasting, telecommunication, radar, remote sensing, navigation, weather detection, and missile guidance systems. Antennas used in these applications have to be characterised in terms of gain, polarisation, axial ratio, pattern and reflection coefficient to ensure that they meet the design specification. The complexity of all but the simplest of antenna designs is often such as to preclude the reliable prediction of performance by calculation and so measured performance is essential, for example for satellite antennas where gain has to be known precisely and mistakes can be very expensive to rectify.

Background
The Electromagnetic Programme has supported the development of range of facilities at NPL. The reconstruction and recommissioning of these facilities in NPL's new laboratory building has enabled significant enhancements to be made, providing the NMS with world leading capabilities for antenna metrology. The facilities include:-

- An 30 x 60m open area test site (OATS),
- An extrapolation range housed in a 7m x 7m x 15m anechoic chamber for antenna calibrations in the range 500 MHz to 100GHz
- A spherical scanning facility for large antenna
- A microwave EMC antenna calibration facility
- A ferrite lined Fully Anechoic Room for antenna calibrations below 2 GHz

Trends
The need to make more effective use of the electromagnetic spectrum to meet the insatiable demand for bandwidth is impacting on the number of antenna deployed and on their complexity. An example of this is antennas for mobile communications where numbers are growing as coverage is extended and new systems are commissioned, and where designs are becoming more complex to increase efficiency and directivity.

Ultra Wide Band (UWB) systems which combine wide bandwidths with low power spectral densities are claimed to increase the utilisation of the spectrum. UWB antenna design remains to be the main challenge in the progress of UWB technology. Characterisation facilities are essential to support the development of UWB antenna while, from a compatibility point of view, it is important to determine the radiation patterns associated with UWB antennas.

There is also a trend towards using larger and higher frequency antennas for satellite systems and scanning antennas for radar and surveillance systems.

Rationale
The rational for projects within this Theme falls into three categories:

Quality of life
The calibration of standard gain horns underpins calibration facilities for Power Flux Density probes in the form of radiation hazard monitors which are used in a wide variety of industrial areas to ensure that exposure to electromagnetic radiation in the working environment does not exceed the levels set out in the NRPB Guidelines.

Regulation
Calibrated antennas are also important to support regulatory aspects of electromagnetic spectrum management and enforcement.

Economic
The calibration of EMC antenna supports about 50 UKAS accredited EMC Test Houses and other accredited calibration laboratories which calibrate EMC antennas. These in turn support the UK electrical and electronics manufacturing sector companies with a turnover of £59B that have to meet the requirements of the EMC Directive.

Reliable measurements of antennas are essential to support the telecommunications sector worth about £5B, and the space technology sector worth about £700M by ensuring that products conform to design specifications and support product innovation.

How projects have been chosen
The scope of the antenna calibration and characterisation theme has been based on current demands for calibration services, the views of UKAS accredited laboratories on future need, and a review of economic and technical trends within published reports. The views of members of NMS FREEMET Club have also been valuable in defining the projects.

Summary of projects

3.1 Standards for RF and Microwave antenna measurements
The project aims to maintain the following measurement standard facilities and associated measurement services for antenna calibration and characterisation from a few kHz to 100GHz.

- Open Area Test Site
- Fully Anechoic Room
- GTEM cell and reverberation chamber.
- Microwave antenna extrapolation range
- Spherical Near-Field Scanning range
- Microwave EMC antenna chamber.

International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

3.2 Development of standards for antenna measurement

The principle objectives of this project are to upgrade the Spherical Near-Field Range to be used as a reference standard range and to extend existing calibration and measurements services to cover intermediate accuracy standard gain horns, wideband EMC horns, rod antennas and monopole antennas not attached to a ground-plane. In addition, a calculable biconical antenna will be developed along with a method for using it to calibrate the antenna factor of other biconical antennas.

4.4 Theme 4: Electromagnetic Field Measurement and Mapping

This theme covers NMS capabilities for the calibration of probes used for measuring and mapping electromagnetic fields in both air and liquids (typically tissue equivalent liquids for Specific Absorption Rate measurements). Included are developments to cover pulsed fields as well as the development of non-invasive field measurement and mapping techniques.

Electromagnetic fields are widely used in industry for drying, food processing and blister packaging, and also for diagnostic and therapeutic uses in medicine. In all of these applications it is essential to ensure that the general public, employees, patients and medical staff are not subjected to more than the acceptable field strengths. Engineers working around radar facilities and transmitting antenna must also be protected from exposure to high field strengths. The National Radiological Protection Board (NRPB) has published its statement on 'Restrictions on Human Exposure to Static and Time Varying Electromagnetic Fields and Radiation' (vol 4, No.5, 1993) which sets guidelines to exposure limits. Traceable measurements of electric field strength and power flux density are essential to protect workers by ensuring that exposure to electromagnetic fields are correctly measured and limits not exceeded.

Calibrated probes for SAR measurements are needed to demonstrate that the radiation from mobile phones is within International Commission on Non-Ionising Radiation Protection (ICNIRP) guidelines for exposure, thus supporting the mobile communications sector and providing reassurance to the 45 million mobile phone users in the UK.

Non-invasive field mapping is an important research tool in electromagnetic standards development and in the telecommunications and defence industries.

Background

The UK NMS supports an extensive range of facilities for the calibration of power flux density and field strength probes at the highest levels of accuracy. Traceability for PFD and Field Strength probes as well as Loop Antennas is realised through a series of calibrated Transverse Electromagnetic (TEM) Cells. In addition, at frequencies above 2.4 GHz a series of calibrated horn antennas with directional couplers is used to radiate a known power onto the probes in an anechoic chamber. Recently, a new chamber has been commissioned to reduce the lower calibration frequency by this method. The facilities and the equipment used for these measurements require regular calibration and auditing to maintain the levels of uncertainty achieved.

New facilities for the calibration of SAR probes at GSM frequencies of 900MHz and 1800MHz, and TETRA frequencies at 400MHz have been developed within the current Electromagnetic Programme. This work has enabled the NMS to provide underpinning dosimetry for the UK Government's MTHR research programme on the effect of mobile phones on health. Previous activities, notably through collaborative research within Europe, has led to the establishment of standard methods for measuring SAR which are now widely accepted world-wide.

Non-invasive field mapping techniques currently available at NPL are based on the Optically Modulated Scatterer (OMS) technique and on an electro-optic field sensor (OEFS). The

OEFS system is particularly well suited to the measurement of time varying fields in fluids while the OMS is excellent for characterising fields close to surfaces. The OEFS can also be used as a small probe for near-field scanning close to an antenna under test, reducing the area of scan plane required.

Trends
Exposure to electromagnetic radiation is currently covered by National Radiological Protection Board (NRPB) guidelines which define exposure limits however within Europe there is a proposal to make exposure limits statutory through a Physical Agents (Electromagnetic Radiation) Directive. This is likely to put even greater pressure on the requirements for traceable measurement of electromagnetic field strengths and power flux density to demonstrate conformance to regulations.

The electromagnetic spectrum is being used to higher frequencies to meet the demand for capacity as described in the previous Themes. The proposed Physical Agents Directive recognises the exploitation of the spectrum to higher frequencies and the draft text of the Directive covers frequencies up to 300GHz.

Mobile communication systems, both voice and data, are also making use of higher frequency bands as these are opened up. Wireless local areas networks (WLANS) currently operate at 2.4GHz and 5GHz is increasingly being used while the longer term rollout of 3G mobile systems will operate at 2.5GHz. These developments are pushing SAR measurements above 1.9GHz currently available.

Rationale

Quality of life
Measurement standards for electric field strength, power flux density and SAR are needed to support current safety guidelines for workers and the public exposed to electromagnetic fields in the work environment and in every-day use of electromagnetic technologies, for example mobile communications, respectively.

Regulation
The proposed work will also enable the UK to have an informed input to the deliberations on the EC Physical Agents (Electromagnetic Fields) Directive, particularly with regard to making practical and reliable measurements of electromagnetic radiation to support regulation.

Electrical field strength probes are also used for EMC testing, hence calibration of these probes also supports regulation falling under the EMC Directive.

How projects have been chosen
The scope of this theme has been based on current demands for calibration services, industry views on future need, the views of probe manufacturers and technical trends within published reports. Current and future regulations on exposure to electromagnetic fields, and the need to support dosimetry within the Government's Mobile Phones and Health Research Programme have also been key factors in defining the projects within this Theme.

Developments within Project 4.2 are defined by the requirements to calibrate probes to higher frequencies and under conditions of actual use, for example pulse fields while those under 4.3

are concerned with extending traceable SAR measurements to higher fields. Project 4.4 is focused on the development of non-invasive fields probes.

Summary of projects

4.1 Realisation of standards for field measurement and mapping

The project aims to maintain Power Flux Density and Field Strength, and SAR probe calibration facilities and associated measurement services. Capabilities for non-invasive field measurement based on the OMS and OEFS systems will also be maintained. International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

4.2 Development of PFD calibration facilities

The aim of the project is to develop the calibration service to meet evolving development in probe technology, specifically to allow calibration factors to be downloaded into instruments. An investigation of probe isotropy and response to pulsed signals will be made leading to the development of calibration service for calibration of probes under pulsed conditions.

4.3 Development of traceable Specific Absorption Rate standards

The aim of the project is to extend SAR probe calibration facilities from 1.9GHz up to 6GHz to cover the 3G, Bluetooth, Wireless LAN and RFID bands, and investigate the effect of signal protocols (i.e. pulsed signals) on measurement uncertainties.

4.4 Field Mapping and Sensing Techniques for Electric and Magnetic Field Detection

The project covers research and development relating to non-invasive opto-electric sensors for improved measurements of fields for applications in SAR and antenna profiling.

4.5 Theme 5: Electromagnetic Compatibility

This Theme covers the development of measurement standards and measurement techniques to support regulations relating to electromagnetic compatibility both for mains harmonics and electromagnetic emission and immunity testing as currently defined under the IEC 61000 range of standards.

Specific topics are on magnetic flux density traceability for non-sinusoidal waveforms, the calibration of harmonic analysers for waveforms with interharmonics and flicker, and validation of alternative methods for EMC testing. Contribution to international specification standards committee deliberations on EMC standards and test methods is an important part of this Theme.

This Theme primarily serves the UK EMC community whose activities underpin trade in virtually all electrical and electronics goods.

Background

International activities aimed at protecting radio services from interference date back to the 1930s, however the most significant event in EMC was the introduction of the EMC Directive in 1995 which requires virtually all products manufactured and sold within the European Community to be certified to have adequate immunity to electromagnetic fields and acceptable levels of emission, that is they should be compatible with the environment in which they are intended to operate. The generally accepted route to achieving compliance is for manufacturers to certify their products as being compliant with agreed international standards. This has resulted in the rapid growth in demand for EMC specification standards and recognised test methods supported by measurement traceability, for example through calibrated EMC antenna.

The EMC Directive also applies to the power environment. Many modern electronic and electrical products draw current from the mains supply in a very non-linear manner, inevitably creating harmonic signals. These distort the mains voltage and create problems for the supply and distribution networks as well as for other equipment connected to the supply. In addition, some products impose fluctuating loads on the mains supply causing lighting to flicker at frequencies which cause human discomfort. Given that the numbers of electronic devices connected to the mains seems set to ever increase, control of harmonic emissions and flicker is a necessary requirement. The European standard EN61000-3-2 specifies limits for flicker and mains harmonic currents up to and including the 40th harmonic of the mains supply, and it is a mandatory requirement from 1 January 2001 that all electrical and electronic equipment having a rated input current less than 16 amps and using a nominal supply voltage of 230V conform to this standard.

The NMS currently provides facilities for the calibration of EMC antenna (see Theme 4) and has made a major input to the specification of EMC test methods and calculation of measurement uncertainties based on the practical and theoretical investigation of measurement techniques using open areas test sites, fully anechoic rooms, GTEM cells and stirred mode cavities (reverberation chambers). Similarly, traceability for steady-state harmonics and a limited class of fluctuating harmonics has been established within the current Electromagnetic Programme.

Trends

The EMC environment is becoming more complex due to advances in electronic technologies and their growing range of application, many safety critical, where unwanted interference could have catastrophic effects.

There is a need to extend EMC emission and immunity testing above 1 – 2GHz as the speed of digital electronics increases without apparent limit. In addition, digital technologies create their own challenges for EMC test methods that remain rooted in analogue technology and whose limits are based on the protection of analogue radio services.

EMC standards have been primarily addressed at products. However, in many circumstances these products are connected to other products with cables that may be unscreened or unbalanced, thus seriously deteriorating their EMC performance. New approaches are required to deal with networked products. Furthermore, the convergence of technologies, for example in multimedia systems, is also challenging EMC testing which in the past has been developed on a products basis.

Present EMC limits have been derived as a result of compromise consensus between interested parties. These limits have taken into account the probability of interference, however with the massive increase in electronic equipment there is a need to reassess the limits.

EMC testing relating to mains harmonics is a more recent development and the standards are still evolving. Recently published standards continue to broaden the scope of measurements to cover an increasing range of regulatory objectives.

Rationale

Regulation

Virtually all electrical and electronic goods manufactured and sold in the European Community must comply with the EMC directive on levels of electromagnetic immunity and emission. Further, equipment having a rated input current less than 16 amps and using a nominal supply voltage of 230V must conform to the extension of EMC directive covering mains harmonics. Reliable measurement for immunity and emission conformance testing as well as for mains harmonics is essential to demonstrate that products conform to the directive and so enable the it to be enforced.

Economic

The EMC Directive effects much of the output of the £47.5B electrical and electronic manufacturing industry in the UK. The costs to industry of demonstrating conformance of their products is significant. The burden is particularly acute for SMEs which may only produce small quantities of specialised equipment - each type requiring an assessment of conformance. Improved, cost-effective methods for conformance testing have a significant financial benefit to industry.

Excessive mains harmonics increase energy losses in the iron cores of electric motors and transformers, and in cables and wires within equipment thus decreasing the efficiency of electrical and electronic equipment. Harmonic currents at triple multiples of the fundamental mains frequency (e.g. 150, 300, 450Hz) in 3-phase supplies create a particular problem; they add in the neutral return, rather than subtracting at 50Hz, so that neutral currents may be unexpectedly large. These effects lead not only to increased energy losses but also to overheating and premature failure of equipment if network and equipment design has not taken account of the presence of harmonics, resulting in significant costs to repair or replace. There are also additional costs in engineering new equipment and networks to cope with increasing harmonics content on the mains supply. With 321TW hours (2 x 10^{12} watt-hours), of electricity consumed each year in the UK, a fractional improvement in efficiency of electrical and electronic equipment through constraining harmonic ‘pollution’ will result in a significant cost saving.

Quality of life
Electrical power, and electrical and electronic devices are an essential part of an industrialised society, its health and safety, general quality of life and much more. The possibility that equipment may not be compatible with each other could have disastrous effects, particularly in safety critical applications. This work, through underpinning the regulations, ensures that equipment is compatible.

How projects have been chosen
The scope of the Theme has been defined following consultation with the EMC Testing Laboratories Association, UK GTEM Users' Group, the UK Magnetic Society, members of NMS clubs and current users of EMC standards.

The work plans of specification standardisation bodies, for example CISPR, have also been a major influence on the scope of the theme to ensure that the UK is well placed to inform deliberations on test methods in support of the interests of UK industry.

Summary of projects

5.1 Magnetic flux and magnetic flux density traceability for new instrumentation and measurement methods
The project aims to develop methods for the extension of the NMS traceability for magnetic flux and magnetic flux density required by modern instrumentation and measurement methods and establish transfer processes to allow calibration of state of the art magnetic measurement systems to the required specification. Dissemination will be through delivery of calibration services and transfer standards, and metrology input to IEC TC 68 WG 2.

5.2 The analysis of waveforms with fluctuating interharmonics and complex flicker applied to the calibration of harmonic analysers
The project will develop a calibration system for IEC61000-4-7 harmonic analysers and Flickermeters accounting for interharmonics grouping and complex flicker. Dissemination will primarily be through delivery of a calibration service for harmonic analysers using harmonic and interharmonics grouping methods as defined in IEC61000-4-7 and a calibration service based on standard flicker waveshapes to calibrate Flickermeters under realistic conditions.

5.3 Developing standards and measurement techniques for EMC
The project aims to support UK industry by developing methods of EMC testing at frequencies above 1 GHz in quasi free-space conditions and in GTEM cells up to 10 GHz. In addition the project will develop techniques to measure the complex reflection coefficient of surfaces using calculable dipole antennas and to calibrate EMI impulse generators. The

outputs of the project will inform deliberations within National Committee meetings for IEC sub-committees CISPR/A and SC77B.

5.4 Advancing the metrology and applications of Reverberation Chambers

The project will develop the understanding and use of Reverberation Chambers for metrology through studies on the characterisation and optimisation of reverberation chambers, and employ such chambers for traceable EMC measurements and for the evaluation of measurement techniques for other free-field parameters including antenna-noise, field-strength probes and total power emitted. The project will continue NMS support for international standards on reverberation chamber metrology.

4.6 Theme 6: Waveform measurements

This Theme provides for a range of industrial measurement requirements ranging from the measurement of single electrical pulses of a few picosecond duration to the measurement of complex waveforms and related parameters.

Signal processing, computing and communications equipment process and/or produce signals that are increasingly more complex. Appropriate measurement techniques for these signals supported by measurement standards are required to demonstrate conformance to specification across the electronics and telecommunications industries.

Background

The NMS provides capabilities for the traceable measurement of picosecond electrical pulses facilitating the calibration of the rise time of fast sampling oscilloscopes and pulse generators down to 7 and 11 picoseconds respectively. Calibration facilities are also available for real-time oscilloscope with bandwidths of a few GHz.

Measurement standards for RF and microwave power have been provided for continuous-wave (cw) waveforms and these have been adequate for simple modulation schemes where signal averaging is performed within the detector to provide a reading of average power. However, the development of more complex modulation techniques has brought about the requirements for non-sinusoidal power measurements. The NMS has responded by providing traceability for peak power and W_CDMA power meters. These capabilities have exploited the synergy of fast scope and cw power calibration capabilities of the NMS.

Trends

Traditionally, many measurements in the electrical domain have been made using cw based techniques. However, these techniques are no longer sufficient to meet the measurement requirements of complex digital equipment. The major drivers are coming from the increasing complexity and speed of digital signal processing and microprocessing circuits made possible by advances in microfabrication techniques, and the sophistication of communication and broadcast technologies aimed at promoting the intensive use of the scarce electromagnetic spectrum.

As the speed of microprocessors continues to increase then the requirement to measure the shape of pulses in circuits becomes more demanding. Within communication technologies, second and third generation mobile systems are using increasingly complex modulation where, for example, the measurement of power based simply on cw techniques is no longer meaningful. The measurement of other parameters associated with digital technologies, for example Bit Error Rate and Jitter, is important, and a new generation of instruments are becoming available to support manufacturing processes, product conformance and diagnostics.

Ultra wideband technology, which uses short pulse radio signals over a frequency range as wide as 7GHz may provide a solution to increasing the utilisation of the electromagnetic spectrum. Measurement techniques will play a significant role in allowing the introduction of UWB technology. As far as the compatibility with other systems is concerned, it is crucial to identify which parameters (for example, pulse width, pulse repetition factor, peak power, rise/fall time) should be used to limit UWB transmissions, what numeric values should apply and which techniques should be used to measure these limits.

As oscilloscopes and data converters are increasingly used for digital signals full characterisation in the time domain is preferable. The time domain also offers potential advantages for high frequency microwave measurements where systems covering different frequency bands may be required, and where a more cost effective and simpler system may be preferable. In summary, the measurement of waveforms is becoming increasingly important as the technology and analysis techniques available demand new or improved measurements or afford opportunities to improve existing NMS facilities using radically different techniques.

The technological growth related to data communications has led to data converters that operate at frequencies above 1 GHz, whilst giving rise to improvements in resolution and accuracy at lower RF frequencies. Such data converters also have the potential to be applied to higher frequency metrology in the RF region. There are potentially a number of areas where established measurement systems can be transformed by replacing analogue components with a data converter. In some cases, this may be an ADC at the front of a system closer to the antenna, replacing a number of analogue components by digitising key signals at the earliest opportunity thus eliminating uncertainties associated with the handling of high frequency signals within the measurement system. In other cases this could be a digitally synthesised signal generator used to replace analogue standards. It is envisaged that the NMS could take advantage of these advances in converter technology to improve RF traceability in a number of areas including the digital synthesis of noise signals for noise standards and the calibration of vector signal analysers.

Rationale

Economic
The projects proposed in this section are aimed at supporting the Information Technology, Electronics and Communications sector – a sector vital to the UK economy in terms of employment and contribution to GDP. In 1998 the UK ICT sector was estimated at 8.6% of GDP, with a total turnover of £181.6B.

The markets for mobile devices are evolving and offer exceptional opportunities for manufacturers and service providers. Specification standards supported by reliable test methods and measurement standards are essential to facilitate innovation in this technology, to reduce barriers to market access by new entrants and to encourage interoperability of new products.

Regulation
In common with current services and applications using the spectrum, ones based on new technologies, which are aimed at making intensive use of the scarce need to be spectrum, need to be regulated to ensure services can coexist and interference is kept to a minimum. Reliable measurement techniques for digital technologies are necessary to help specify numerical limits to operational parameters and define associated test methods, and provide a means of monitoring them.

How projects have been chosen

The scope of activities in this Theme has been determined through the recommendations of the Electromagnetic Programme Orientation Report, discussions with instrument manufacturers and instrument users in the IECT sector, technical and economic trends within published reports, particularly within ‘Foresight’, and technical stemming from the need to promote the development and introduction of electromagnetic spectrum-saving technologies.

Projects 6.1 and 6.2 provide traceability for fast electrical pulses whilst Project 6.3 addresses the measurement needs of digital communication technologies. Project 6.4 is applying time domain techniques to measurements in this area. Project 6.5 is applying digital technologies to providing new solutions to RF measurement problems.

Summary of Projects

6.1 Standards for electrical pulse measurement

Capabilities for the calibration of pulse generator risetime to 11ps, pulse generator amplitude and pulse aberrations, electrical sampling oscilloscope risetime to 7ps, and electrical delay lines will be maintained. Input will be made to standardisation committee IEC TC 85 on a new risetime standard based on IEEE P181.

6.2 Development of standards for electrical pulse measurement

The project aims to develop capabilities for the calibration of electrical pulse generators risetime down to 5ps, time and frequency domain facilities for >75GHz electrical sampling oscilloscopes, reference receivers and photodiodes, and >4GHz real-time oscilloscopes.

6.3 Measurement standards for digital communication (Datacomms)

The project aims to undertake research into techniques for the traceable measurement of Bit Errors Rate and Q-factor, EMV, ER, SNR and jitter, and apply there results to provide measurement support in the Datacoms area for jitter and wander in WLAN, SDH/SONET and Gigabit Ethernet. The project outputs will also inform deliberations within IEC and ITU standardisation committees.

6.4 Application of time domain techniques to RF and Microwave metrology

The project aims to apply time domain techniques to complement and improve several areas of RF and microwave metrology, specifically in supporting power/time template standards for digital communication systems and supporting the future measurement needs of UWB technologies.

4.7 Theme 7: Electromagnetic Material Standards and Measurement

This theme covers the measurement of dielectric materials, magnetic materials and structured electromagnetic materials by providing traceable measurement techniques, particularly in the most demanding, innovative applications, supported by reference materials.

Knowledge of the dielectric properties of materials is important to a wide range of industrial sectors including food processing, pharmaceuticals, defence and telecommunications. Similarly, the properties of magnetic materials are important for sensor and actuator technologies in the motor industry, magnetic media in IT, and transformer cores in the electrical and electronics industry

The dielectric properties of tissue equivalent materials are important for SAR standards (see Theme 4) to ensure that safety guidelines on exposure to electromagnetic radiation can be followed, and to support the therapeutic use of electromagnetic radiation.

Background

The NMS already provides traceable measurement capabilities for a range of electromagnetic materials in the frequency range 1kHz to 100+GHz. This is supported by a database listing the dielectric properties of several hundred materials and samples of reference materials. The capabilities have been recently extended to allow thin films to be characterised and work is currently being undertaken to characterise materials for future frequency-agile telecoms technologies within an EC Framework V project on development of tuneable filter materials supported by UK and European telecom companies.

The dielectric measurement facilities have also been applied to measuring the dielectric properties of tissue equivalent materials to support the NMS calibration facility for SAR probe calibration at 400, 900 and 1800MHz. This work also underpins the dosimetry within the Government's MTHR programme to study the possible health effects of electromagnetic radiation from mobile phones.

NMS activities within the field of magnetics have led to the development of capabilities to characterise some magnetic materials and provide reference standards.

The NMS activities in this area have enabled the UK to contribute standardisation committees, for example CENELEC and IEC, dealing with the dielectric and magnetic properties of materials, and the knowledge is disseminated through the NMS Electromagnetic Materials Measurement and Applications Club and the UK Magnetics Society.

Trends

The performance of electronic components and systems is critically dependent upon knowledge of the magnetic and electromagnetic properties of the materials from which they are constructed.

New requirements to characterise thin and sub-micron films are emerging both in new substrate/packaging technologies and in advanced technical applications in the nanotechnology and biotechnology fields. The general move to higher frequencies generates a need for characterisation of smaller, higher-permittivity dielectric resonators and also generates requirements for new transmission line technologies – such as dielectric waveguide which can be used all the way up to THz frequencies. The materials interest here is to discover to what extent the microwave, millimetre-wave and THz can emulate the performance of optical-fibres, for example by using graded-index dielectric waveguide to reduce propagation loss.

Requirements for smaller electronic devices also promote requirements for higher circuit packing densities. One example of this is the introduction of multilayer substrate LTCC (Low Temperature Co-fired Ceramic) technologies where there is a need for better techniques to characterise these materials, both alone and in co-fired circuits.

Traceable electromagnetic field dosimetry – the main health and safety concern associated with broadcast technologies - is likewise wholly dependent upon accurate measurement of the electromagnetic properties of materials. 3-G, Bluetooth, wireless-LAN technologies are finally emerging into the marketplace and bring with them a requirement for traceable SAR measurements over a wider frequency range than currently available in the NMS - at least up to 5 GHz in the short term. The latest development is a draft EC Directive for limitation of public and occupational exposure to electromagnetic fields. If it accepted by member states, it will place more demands upon the NMS for traceable SAR measurements.

The wide field of structured materials continues to advance, largely enabled by parallel improvements in its associated numerical modelling. A new science of 'metamaterials' has been created, in which the UK is one of the leaders. It deals with structures that include 'negative-refractive index materials', 'left-handed materials' 'photonic band-gap materials', 'frequency selective surfaces' and 'phase conjugate materials'. The functional interest is in the generation of useful artificial material properties (such as negative refractive index) that are not available from homogeneous materials. Over the last decade there has been considerable interest from the defence sector in these metamaterials, for example. for stealth and beam filtering functions, and applications are now being transferred to the civil sector with promising applications in UK industry. The metrological requirements here are two-fold; the characterisation of the metamaterials and the design and use of metamaterials to improve uncertainties in other areas of electromagnetic metrology.

Rational

Economic

Materials are at the heart of the UK's £4.4B electronic components manufacturing industry and support the wider electrical and electronic equipment-manufacturing sector. The UK Government's Foresight Sector Panel on Materials has recognised the importance of materials in underpinning key technologies and has recommended that increased resources should be devoted to R&D and exploitation in, amongst other things,:-

- Better materials to serve the needs of the mobile IT and telecommunications industries.
- Improved testing and evaluation methods to generate good data to test models which relate materials composition, structure, process parameters, end product performance and design.
- Materials to improve sensors and devices.
- A new generation of biomaterials which encourage and enhance the restoration and repair of body tissue function

The ability to characterise materials in a reliable way is essential to facilitate innovation in design and exploitation of novel materials and ensure their technical and economic success.

Quality of life

Accurate knowledge of the dielectric properties of tissue equivalent materials is required to support dosimetry of electromagnetic radiation to limit exposure and to support the research activities within the Government's MTHR programme investigating the health effects of mobile phones.

How projects have been chosen

The scope of activities in this Theme has been based on current demands for calibration services, the views of expert members of the NMS Electromagnetic Materials Measurements and Applications Club and the UK Magnetic Society, and technical and economic trends within published reports. Consideration has also been given to the requirements of CENELEC, IEC and IEEE standardisation committees, and of the MTHR research programme and of the proposed Physical Agents (Electromagnetic Radiation) Directive.

Summary of projects

7.1 Maintenance and development of Electromagnetic Materials Measurement capabilities

The project aims to maintain existing facilities and provide calibration services for dielectric, magnetic and conductivity measurements on materials. International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

7.2 Measurement of the magnetic properties of soft magnetic materials for operational non-sinusoidal waveforms

The project aims to develop traceable measurement capabilities for determination of specific total loss and peak permeability of soft magnetic materials for operational non-sinusoidal waveforms with target uncertainty of 1%, and to inform the deliberations standardisation committee IEC TC86 WG2.

7.3 Electromagnetic materials metrology for industry

The objectives of the project are to develop facilities for traceable characterisation of microwave ferroelectrics, to research techniques for broadband characterisation of very low-loss dielectric resonator materials in the range 300 MHz – 6 GHz to support the UK mobile telecoms and filter industries, and to establish new techniques and construct cells to measure traceably the dielectric properties of micron-scale thin films and small-cross-section specimens.

7.4 Dielectric Measurements for health and safety

The aim of the project is to improve the accuracy and frequency range of the dosimetry of broadcast electromagnetic radiation by a factor of two and up to 6GHz respectively, and support the mobile communications industries by researching new homogeneous phantom materials and characterising reference materials for SAR testing.

4.8 Theme 8: Laser Power and Energy Standards

This theme supports the realisation and dissemination of standards laser for power and energy from the infrared to the UV. Also included in this theme are developments in specific areas to meet evolving industry needs for lower uncertainties and/or increased range of measurement. The projects in this theme will transfer to the Optical Radiation Metrology Programme and the Photonics Metrology programme on 1 April 2004.

These measurement standards support lasers of different types operating at wavelengths in the infrared, visible and ultra violet (UV) which are used widely in manufacturing for cutting and welding, in medicine for surgical procedures, in defence for range finding and target identification, and in a wide range of other applications ranging from precise measurement to laser light shows. The standards also support safety directives on classification and operation of lasers.

Background

Secondary standards for laser power at NPL up to 150W are calibrated against the cryogenic radiometer. Energy standard calibration incorporates use of these power standards and traceability to national frequency standards.

Trends

Industrial laser usage is now commonplace in many sectors, from engineering in automotive and aerospace industries to precision microelectronics, micro (opto)electro-mechanical systems MEMS/MOEMS and micro-optics. Lasers are also becoming widely used in medical applications such as surgical procedures and drug related therapies.

Developments in the applications of lasers in industry are producing increasing demands for accurately characterised laser beams. Examples include high precision hole drilling at both the macro scale in large scale engineering to reduce wastage and at the nano level where UV lasers are employed to modify phase masks for semiconductor manufacture, or to construct precision medical devices with nanometre accuracy. The standard approach of quality control by inspection of finished work is fast being replaced by online monitoring of laser parameters to ensure that the material-laser interaction at the work piece is optimised.

Current laser safety regulations do not effectively address the possible hazards due to the complex phase coherence factor and the beam width in an optical system. The establishment of reliable measurement methods and test instrumentation for these parameters is essential for accurate risk assessment. There are at least five international standards that are beginning to consider this omission.

The increased interest in the use of Free Space Optics (FSO) as a method of transmitting data is due to its ease of installation especially in urban environments where cable-laying operations are difficult due to disturbing the existing local infrastructure, people or the environment. Also, RF bandwidth is restricted and expensive, so FSO has the benefit of a substantial bandwidth that does not require licensing. Wavefront sensing is an essential measurement for the continuous optimisation of this transmission process.

Rationale

Economic
Reproducible means of characterising laser beams used in industry and medicine is important for controlling the quality of manufacturing processes and medical procedures respectively. Consumer goods increasingly incorporate laser technology and the safety of these devices needs to be rigorously established using traceable measurement.

Quality of life
Laser power and energy standards underpin health and safety directives on laser classification and operation within internationally agreed standards, for example ISO 60825 parts 1 and 2 (laser safety standard).

How projects have been chosen

The scope of activities to provide standards for laser power and energy has been based on current demands for calibration services, trends in instrumentation through dialogues with instrument manufacturers and users, developments within standardisation committees and a review of technical and economic trends within published reports.

The views of members of the NMS ‘Foton’ Club and of the Association of Industrial Laser Users have also been valuable in defining the projects.

Summary of projects

8.1 Provision of traceability for laser power and energy measurements

The objective of the project is to provide calibration facilities for the measurement of laser power and energy at discrete wavelength points encompassing power levels from 1 mW to 100 W and energy levels from 1 nJ to 1 J, and establish new calibration services for laser test instrumentation for low energy levels and for optical peak powers of pulsed sources. International comparison of key quantities arranged under the auspices of the BIPM or EUROMET, and knowledge transfer activities related to specific technical activities are also included.

8.2 Laser wavefront sensing

The aim of the project is to develop techniques for the traceable measurement of laser beam parameters, in particular to establish a characterised reference wavefront source, a capability for the calibration of laser wavefront instrumentation at discrete wavelengths over the range 532 nm to 1550 nm., and a capability for calibration of laser beam spatial profiling devices and also beam propagation parameter devices (M^2 parameter). The project would also investigate the feasibility of applying cw laser wavefront techniques for characterising Frequency Resolved Optical Gating based measurement systems.

4.9 Theme 9: Future Technologies

This Theme concentrates on areas of research and development which are anticipated to have an important impact both on measurement capabilities and/or measurement requirements in 3 – 6 years. Such areas are nanoscale electronic devices and microelectromechanical devices which have significant potential to improve the accuracy with which electrical quantities are realised as well as creating their own requirements for measurement capabilities on a scale appropriate to the devices, for example for very small currents or capacitance. Typically, this research is challenging and forward looking in character.

The theme also addresses the emerging requirements for electrical standards and measurement techniques within biotechnology and terahertz technologies; two fields in which the UK has significant strengths.

Background

The two most significant advances in electrical measurement - the realisation of the volt and ohm in terms of quantum phenomena - are due to microfabrication technologies which have allowed arrays of Josephson junctions and quantum Hall devices to be realised. Devices fabricated on a nanometre scale enable single electrons to be manipulated and counted, holding the promise of a quantum standard of current. The NMS Quantum Programme has supported work at NPL to develop and evaluate such devices, largely in collaboration with UK academia and other research organisations within Europe. The projects within this theme build on present achievements and applying them to practical measurement problems as well as making them more accessible.

Advances in microfabrication technologies have enabled microelectromechncial devices to be developed and such devices are already finding widespread application, for example as sensors in car safety airbags. Recently, MEMs-based applications have been developed for electrical metrology. Although MEMs lack inherent quantum accuracy, they can be made extremely sensitive (by reducing the size) and are ideally suited for the development of new low cost, high accuracy standards which could be incorporated into commercial instruments. MEMs are now being used in the RF and Microwave sphere where there is considerable industrial and research effort going into MEM switches. However for MEMs-based RF and Microwave metrology, other MEM devices are required, for example membranes, cantilevers, force-balance devices, V-groove alignments, micro-coaxial electrical connections. These are not nearly so advanced in their development, so by focussing on carefully selected projects with world-leading collaborators in this field, the NMS should be in a good position to take a lead in this field.

Electrical measurement is expected to be important in biotechnology as it is for virtually all other areas of technology, for example electrical connections and measurement of currents within molecules and through membranes will be important for studying biological materials and for developing bio-sensors.

The terahertz region of the electromagnetic spectrum, between the microwave and optical regions, has recently started to be exploited commercially with the development of terahertz sources with sufficient useful power. Applications include medical and security imaging, and NDT.

Trends

Nanotechnology and Biotechnology are widely regarded as important technologies for the future. The Foresight Futures 2002 Report highlights these technologies as amongst the fastest growing sectors and EPSRC and DTI are promoting activities in these areas to ensure that the UK remains competitive in this field.

Specifically within electrical nano-technology two generic approaches can be identified. Firstly, the well-established top-down approach in which nano-electrical circuits are produced by lithographic techniques has been very successful in the past and resulted in an array of new fundamental effects. The metrological community can now exploit this new technology by developing novel metrological applications and instruments. Two proposed projects will focus on such developments. Secondly, the bottom-up approach in which self-assembly of single atoms or molecules is used to create functional devices. Clearly the latter approach is very challenging and long term. Today, even hybrid approaches are being developed in which nano-patterned circuits are being used to capture single molecules. These hybrid techniques are becoming increasingly important in biotechnological applications. The ability to study individual atoms and molecules is potentially of great value to the understanding of biological processes at the most basic level that in turn could lead to analysis or measurement techniques based on them. The NMS can contribute to this important area by developing the necessary skills and technology to measure electrical or magnetic signals from individual molecules and a related project is proposed.

At RF and Microwave frequencies, trends in the electromagnetic industrial sectors are towards ever smaller, wider-band components and higher frequency technologies. The NMS is faced with the metrological problem of servicing an industry that wishes to preserve measurement accuracy for quality control purposes and yet is increasingly working at frequencies and size-scales that unavoidably introduce greater measurement uncertainties. The solution may be found by moving to new metrological and signal handling technologies. Among those which will be central to projects proposed here are those of Micro Electro-Mechanical (MEMs) and micromachining. The trend towards smaller component sizes and exploitation of ever-higher frequencies has prompted microwave companies to manufacture extremely small coaxial lines - down to 1 mm diameter, with 0.5 mm planned. With conventional technologies there is no prospect that the NMS can produce traceable impedance standards for such line sizes at frequencies up to 100 GHz but micromachining and MEMs offer ways forward here, as does the use of dielectric waveguide.

The proliferation of services and uses of the electromagnetic spectrum is such that there is no part of the spectrum that is unallocated at the international level below 275GHz. The task of finding spectrum for new applications below this frequency is extremely difficult and, as described in previous sections, new technologies are being exploited to maximise the use of the spectrum. A region of the spectrum that has been little exploited is the Terahertz region between microwave and optical frequencies. However, the development of suitable sources and detectors operating at Terahertz frequencies is now opening it up to commercial exploitation. Some of the applications include medical imaging, security and non-destructive testing.

Justification

Two main issues have to be addressed for nanotechnology to be successful in future applications 1) A number of quantum physical properties are very interesting for industry and metrology, however linking these sensitive effects on the microscale to real macroscopic applications will need significant advances in measurement technology. 2) Most quantum effects observed today occur at extremely low temperatures which severely hamper their usability and is a main obstacle for industry buy-in.

MEMs devices have already found wide application. For example, almost every new car has MEMs based sensors in the airbags. The benefit of this mature technology is that the principles of MEMs devices are well understood and that reliable fabrication facilities are readily available at relatively low cost. An additional important feature of MEMs devices is that their application is not limited to low temperatures. Over recent years a number of MEMs based applications have been developed for electrical metrology. Although MEMs lack inherent quantum accuracy, they can be made extremely sensitive (by reducing the size) and are ideally suited for the development of new low cost, high accuracy standards which could be incorporated into commercial instruments. MEMs are now in the RF and Microwave applications where there is considerable industrial effort going into developing MEMs switches. However for MEMs based RF and Microwave metrology, other MEMs devices are required, for example membranes, cantilevers, force-balance devices, V-groove alignments and micro-coaxial electrical connections.

The fabrication techniques developed for MEMs can also be used to address issues in impedance measurement where the increase in frequency has made the manufacture of components impossible.

How and why projects have been chosen

The technologies in this Theme have been chosen based on the important emerging technologies identified in the Government's Foresight consultations and reviews, and the relevant technology trends identified in the Orientation Study.

The individual projects have been chosen to develop the metrological knowledge in these important technologies to support industry and Government decision making, to position the NMS to provide measurement capabilities to support innovation and quality control in manufacturing in the exploitation of these technologies, and to apply these novel technologies to improve measurement accuracy in established areas of metrology.

There are very significant benefits in undertaking collaborative projects, particularly in new technologies where knowledge and expertise my rest in academia, research organisations and 'incubator companies'. Collaboration also provides a route for disseminating the knowledge developed within a project. Hence, a factor in choosing projects has been the opportunities to undertake the projects collaboratively.

It is expected that many of the projects within this Theme would be undertaken within a framework of collaboration between NPL, academia, other National Measurement Institutes and research organisations, and industry.

Project Summaries

9.1 Integration technologies for single quantum devices

The objective of the project is to develop single electron tunnelling devices for operation at temperatures of 4.2K or higher along with supporting instrumentation to measure the parameters at the quantum limit.

9.2 Application of electron transport devices to generation and scaling of small electrical currents

The project aims to research current standards based on quantum units and verify the consistency between 1nA, 1nF and 1GΩ at the 1ppm level. Within this project, a current ratio device for the generation of small (pA) currents with exact frequency controlled ratios based on the transport of single electrons by surface acoustic waves will be developed.

9.3 Quantum standard of alternating voltage based on the Josephson effect

The aim is to research and develop the application of the Josephson effect to the synthesis and measurement of precision time-dependent voltages at frequencies up to 100 kHz, and to develop the theory of the dynamic behaviour of Josephson junctions and to fabricate new array designs based on this theory. The project would be undertaken in collaboration with an institute with array design and fabrication skills.

9.4 Metrology for the Terahertz (THz) frequency band

The object of the project is to establish new capabilities for metrology in the Terahertz region of the electromagnetic spectrum; initially through the provision of traceability for power measurement in the 0.3 to 20THz region and dispersive Fourier transform techniques for material characterisation in the terahertz band. Supporting activities on investigating new devices for the generation, detection and guiding of signals in the terahertz band will be undertaken.

4.10 Theme10: Knowledge Transfer

The activities in this theme can be divided into two areas, promotion and knowledge transfer.

UK industry can be viewed as two key groups, the inner and outer circles. The inner circle is defined as current contacts who work closely with the individual technical projects through activities such as collaborative research, industrial visits, technical publications and presentations. The outer circle is defined as all other potential beneficiaries for the programmes. Knowledge transfer to this outer group aims to ensure they know where to come with technical problems and encourages them to become directly involved with the technical projects (the inner circle).

Promotion ensures that there is awareness that the programme exists to both the outer and inner circle members who are not yet directly involved and provides a route for them to become involved. Promotion also ensures awareness of project outputs (guides, databases, workshops etc.). Activities included in this area are newsletter articles, liaisons with trade associations and professional bodies, press releases, flyers, websites, trade articles, direct mailings etc. This activity will be ongoing throughout the programme.

Knowledge transfer typically takes place through the middle and later stages of the programme, as the knowledge must be developed before it can be transferred. Direct knowledge transfer is to the inner circle through activities including case studies, trials, clubs, and measurement services. Knowledge Transfer to both the inner and outer circles may be through guides, databases, reports, papers, articles etc.

It is widely recognised that direct contact between research and industry provides the most effective means of knowledge transfer. This will be facilitated through training clubs, courses, workshops, secondments, visits, and collaborative working. This direct contact also enables industrial need to be fed back into the technical programme.

The industrial benefit from the knowledge transfer theme will be ongoing throughout the duration of the programme. Early in the programme benefit will be realised by companies becoming aware of the work enabling them to become directly involved. Companies who have direct involvement with the technical projects will receive the greatest benefit. As the programme progresses knowledge transfer will be facilitated from all technical projects. This project will assist with this industrial transfer as well as providing vehicles for it to happen i.e. technical clubs. This project will also package details from several projects that may be relevant to one contact/industrial group.

The assessment of the impact of the Programme will be evaluated within this theme.

Background

During the NMS Electromagnetic Programme 2000 - 2003, knowledge transfer has taken place through technical clubs, training courses, web pages, newsletters, conferences, as well as international intercomparsions and liaisons. An advisory service provides a one-stop-shop for information from the programme receiving hundreds of enquires per year. Knowledge transfer from the individual scientific projects is completed through technical presentations, reports, visits, technical papers and representation on relevant committees. The technical clubs provide a forum for industry / research interactions through events, publications and direct meetings.

This project will build on the previous knowledge transfer and continue to facilitate the uptake of results from the NMS Electromagnetic programme by UK industry. To ensure that all KT continues to be effective industry will be divided into sections, as outlined in the rationale, and the most appropriate KT mechanisms for each audience employed.

Rationale

The Government's 2000 White Paper on science and innovation noted, "*knowledge must flow out of the science base into products and services. All industries will benefit from this knowledge flow, from basic manufacturing and food processing, to the new science-based industries of the future*". In addition to benefiting from this knowledge, easy access to publicly funded research will enable companies to develop competitive advantage.

Recommendations from the Foresight Manufacturing 2020 Panel highlight the importance of knowledge transfer in enabling UK manufacturing to compete on the global stage. The need for actively matching business needs with key research programmes is demonstrated. The requirement for learning provision through training development meeting industrial needs is also highlighted. In particular the mechanism for SMEs to take advantage of such initiatives must be considered.

The work in this proposal aims to address these issues and ensure that information and knowledge generated in the NMS Electromagnetic programme is transferred to industry in an efficient and effective manner. This work will ensure awareness of the entire programme as well as assisting with effective KT from the individual projects.

How and why projects have been chosen

Projects have been chosen on the basis of feedback from current members of NMS Clubs in the electromagnetic area, discussions with the managers of the NMS KT Programme, and observation of 'good practice' in other programmes and wider.

Project summaries

10.1 Knowledge transfer

The project will maximise the impact of the entire NMS Electromagnetic Programme on industrial productivity for relevant sections of UK industry through the most effective means possible, including Clubs, advisory services, Conferences and Workshops, and publications and newsletters. Partnerships with related bodies, programmes and industrial groupings will be developed to maximise the impact of the programme and therefore the uptake of the work. Continued evaluation, and working with other KT initiatives, will ensure best practice is developed and used in all aspects of knowledge exploitation.

4.11 Theme 11: Programme Management

This Theme covers the overall co-ordination functions for the Electromagnetic Programme, quarterly and annual reporting on progress, and general liaison with NMSPU. This will include monitoring the progress of all projects, liaison with NMSPU on all technical and financial matters, and proposals to NMSPU for programme modifications arising from technical outputs and changing industrial priorities.

The value of the programme and its industrial impact can be maximised in all technical areas through collaboration with industry and academia, and other National Measurement Institutes and research organisations. Management activities will identify and pursue these opportunities.

The Theme also covers the formulation of the 2006 - 2009 Electromagnetic Programme by a process involving detailed consultation with a cross-section of the customer base, via meetings, studies, surveys and visits, and via consultation with technical experts in the UK and internationally. It is anticipated that the draft programme document will pass through a similar process of public consultation, modification, and then appraisal and prioritisation by DTI and its industrial advisory group.

Abbreviations

AC	Alternating Current
ADC	Analogue-to-Digital-Converter
ANA	Automatic Network Analyser
ANAMET	Automatic Network Analyser Metrology Club
BER	Bit Error Rate
BIPM	International Bureau of Weights and Measures
BSI	British Standards Institution
CCEM	Consultative Committee on Electricity and Magnetism
CENELEC	European Committee for Electrotechnical standardisation
CIPM	Comité International des Poids et Mesures
DC	Direct Current
DTI	Department of Trade and Industry
EA	European Accreditation
EMC	Electromagnetic Compatibility
EMMA	Electromagnetic Materials Measurement and Applications Club
EUROMET	European Metrology Network
EUT	Equipment Under Test
FAR	Fully Anechoic Room
FREEMET	Free Field Metrology Club
IEC	International Electrotechnical Commission
ISM	Industrial, Science and Medical
ISO	International Standards Organisation
ITU	International Telecommunciations Union
LF	Low Frequency
LAN	Local Area Network
LTCC	Low Temperature Co-fired Ceramic
MEMS	MicroElectroMechanical
MTHR	Mobile Telecommunications and Health Research
NIST	National Institute of Standards and Technology
NMI	National Measurement Institute
NMS	National Measurement System
NMPSU	National Measurement System Policy Unit
NPL	National Physical Laboratory
NRPB	National Radiological Protection Board
NSA	Normalised Site Attenuation
OATS	Open Area Test Site
OIML	International Organisation for Legal Metrology
QHE	Quantum Hall Effect
OMS	Optically Modulated Scatterer
PFD	Power Flux Density
RAM	Radio Absorbing Material
RC	Reverberation Chamber
RF	Radio Frequency
SAR	Specific Absorption Rate
SDH	Synchronous Digital Hierarchy
SI	Systèm International
SME	Small to Medium Enterprise
TEM	Transverse Electromagnetic
TETRA	Terrestrial Trunked Radio

UKAS	United Kingdom Accreditation Service
UWB	Ultrawideband
WLAN	Wideband LAN

Project Titles

Theme 1: Direct Current and Low Frequency Electrical Standards

1.1 Realisation and dissemination of DC and AC standards at frequencies up to 1 MHz
1.2 Development of DC and AC standards at frequencies up to 10MHz
1.3 Development of a calibration service for power measurement under non-sinusoidal conditions

Theme 2: Radio Frequency and Microwave Electromagnetic Standards

2.1 Realisation and dissemination of RF and Microwave standards
2.2 Development of RF and Microwave guided wave standards
2.3 Extend existing national impedance standard capabilities at microwave frequencies
2.4 New impedance standards for millimetre wave frequencies
2.5 Measurement assurance techniques for industrial microwave impedance calibration facilities
2.6 Development of measurement techniques for calibration of high frequency impedance analysers
2.7 International measurement reference for on-wafer calibrations

Theme 3: Antenna Calibration and Characterisation

3.1 Standards for RF and Microwave antenna measurements
3.2 Development of standards for antenna measurement

Theme 4: Electromagnetic Field Measurement and Mapping

4.1 Realisation of standards for field measurement and mapping
4.2 Development of PFD calibration facilities
4.3 Development of traceable Specific Absorption Rate standards
4.4 Field Mapping and Sensing Techniques for Electric and Magnetic Field Detection

Theme 5: Electromagnetic Compatibility

5.1 Magnetic flux and magnetic flux density traceability for new instrumentation and measurement methods
5.2 The analysis of waveforms with fluctuating interharmonics and complex flicker applied to the calibration of harmonic analysers
5.3 Developing standards and measurement techniques for EMC
5.5 Advancing the metrology and applications of Reverberation Chambers

Theme 6: Waveform measurements

6.1 Standards for electrical pulse measurement
6.2 Development of standards for electrical pulse measurement
6.3 Measurement standards for digital communication (Datacomms)
6.4 Application of time domain techniques to RF and Microwave metrology

Theme 7: Electromagnetic Material Standards and Measurement

7.1 Maintenance and development of Electromagnetic Materials Measurement capabilities
7.2 Measurement of the magnetic properties of soft magnetic materials for operational non-sinusoidal waveforms
7.3 Electromagnetic materials metrology for industry
7.4 Dielectric Measurements for health and safety

Theme 8: Laser Power and Energy Standards

8.1 Provision of traceability for laser power and energy measurements
8.2 Laser wavefront sensing

Theme 9: Future Technologies

9.1 Integration technologies for single electron devices
9.2 Application of electron transport devices to generation and scaling of small electrical currents
9.3 Quantum standard of alternating voltage based on the Josephson effect
9.4 Metrology for the Terahertz (THz) frequency band

Theme 10: Knowledge Transfer

10.1 Knowledge transfer

Theme 11: Programme Management