NATIONAL MEASUREMENT SYSTEM PROGRAMME FOR ACOUSTICAL METROLOGY

October 2004 to September 2007

Final Programme Document

FORMULATED BY THE NATIONAL PHYSICAL LABORATORY
ON BEHALF OF THE NATIONAL MEASUREMENT SYSTEM DIRECTORATE
OF THE DEPARTMENT OF TRADE AND INDUSTRY

July 2004

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Executive Summary

The vision

Laying the foundations for revolutionary new MEMS-based miniature wireless acoustical measuring instruments and optically based calibration methods are the two main thrusts of this proposed 2004-2007 NMS Acoustical Metrology Programme. About 13% of the programme spend will be devoted to these important new long-term developments whose combined aim is to revolutionise acoustical measurement by providing the industrial, commercial and environmental user of noise measuring equipment with new, cheap, easy-to-use and versatile instrumentation of UK origin which will overcome most if not all of today's measurement problems.

Overview of the document

This document outlines the proposed 2004-2007 NMS Acoustical Metrology Programme. It presents requirements that have been identified during a range of consultation processes followed by prioritisation and decision making processes. The programme content as listed in Annex B. The aim of this document is to set down the proposed requirements for projects and sub-projects with their rationales and justifications that gives maximum benefit to industry both now and in the medium and long term future.

Programme rationale

Measurements of acoustical quantities are made very widely, by companies in manufacturing and service industries, authorities responsible for occupational and environmental health, hospitals and clinics, and by defence services, for many different applications. Examples include the noise emitted by sources such as aircraft and industrial machinery, the noise exposures of workers in their occupational environment and the general public where they live, individual persons' hearing sensitivity, the ultrasonic sound energy produced by medical therapeutic and diagnostic equipment and by industrial devices such as ultrasonic cleaning baths, and the sound fields radiated or received by underwater acoustical systems. The purposes of the measurements include the collection of information for product specifications and contracts, demonstration of compliance with regulations, access to markets, assessment of public nuisance, comparison with safe exposure limits, ensuring accurate diagnosis and effective therapy, and enabling accurate underwater positioning, mapping and detection.

The principal objectives of the NMS Acoustical Metrology Programme are:

- to provide, develop and disseminate primary acoustical standards for realising the pascal for sound in air and water;
- to ensure that UK measurement standards in acoustics are harmonised with those of the UK's trading partners;
- to develop innovative new methods of measurement for sound, noise and ultrasound to meet identified UK private and public sector needs, and promote international standardisation of these methods;
- to promote knowledge transfer from the programme and the adoption of good measurement practice.

Vision and longer-term plan

The NMS Acoustical Metrology Programme has supported the realisation and dissemination of primary measurement quantities, the most important being the pascal, which have and still provide the wide range of users with the key traceable measurements demanded by regulation or specification standards.

Increasingly, the requirements of the user are such that conventional measurement methods are inadequate to meet needs. For example, some of the challenges in acoustical measurement include:

- airborne noise measurement in complex machinery environments
- spatial sampling limitations in machinery and environmental noise measurements
- accounting for environmental influences during environmental noise measurements
- making reliable measurements in rooms (dwellings), especially at low frequency
- in-ear acoustic measurements
- characterising high power ultrasonic fields
- noise measurement in underwater acoustics
- increased sophistication of cheap measuring instruments.

Solutions to these challenges may be varied but a common feature in most of them is that there is a need for a 'grass-roots' approach to the development of new measurement methods. This approach has previously been successfully adopted by the NMS in other areas of acoustics. For instance, the original development of the membrane hydrophone was necessary in order to provide a gold-standard measuring device for medical ultrasonic fields. More recently the development in the 2001-2004 NMS Acoustical Metrology Programme of the novel sensors for detection of cavitation address the need for measurements in ultrasonic cleaning baths etc. For underwater acoustics, the recognition that measurement standards need to be realised over the range of ocean conditions led to the NMSD establishing the Acoustic Pressure Vessel facility at NPL. There is now a pressing need to address the very significant challenges outlined above in airborne sound.

When faced with the above measurement challenges, the limitations of current measurement methods in airborne noise measurements lead to uncertainties, often lack of reproducibility, and measurement problems in these 'real world' situations that are often at the level of many decibels. This contrasts with current acoustical metrology that has developed to a level of sophistication such that high calibre measuring instruments are available backed by international specification standards that are highly developed and between them are capable of giving results to less than a decibel. However, whilst these low uncertainties can be realised in many 'well-behaved' measurement situations, increasingly the measurement challenges are the dominant limiting factors in industrial and environmental noise measurements. Furthermore, the challenges of cheap measuring instruments combined with the cost of employing skilled personnel, etc., are increasing the pressures to consider alternative technologies. Although many of the measurement challenges can be overcome by using a larger number of measuring devices deployed in known positions, this is often prohibitive because it is costly, cumbersome and time consuming.

To meet these challenges, it is proposed to embark on realising a vision for a new generation of multi-variable acoustical measuring instruments, based on silicon MEMS technology and wireless communication, to produce cheap, robust, easy to use and deployable systems. A key feature of these proposals is that they are based on UK developments and fully expected to lead to major new commercial opportunities for instrument manufacture in the UK. Such sensor systems will not only revolutionise noise measurement but will provide a large number of new opportunities. For instance, examples would be the deployment of linked arrays of sensors for long-term environmental noise monitoring, grouping of large arrays of sensors around noisy machines, monitoring and controlling noise emissions etc. To realise this new vision, the requirements set out in this NMS Programme are first to establish a 'matchbox sized' basic acoustic pressure sensor with wireless technology through collaborative projects involving academia and industry. Realising smaller-sized devices and additional variable sensing etc. will be achieved either in follow-up programmes or if possible more rapidly through parallel programmes where funding from other sources (industrial and government) will be sought and can be secured.

These new initiatives whereby the whole MEMS technology is the cornerstone of a new range of revolutionary measuring instruments is by its very nature a disruptive technology, undermining long-standing markets based on old technology. Hence, there are real positive opportunities for the programme to facilitate the shifting of the knowledge base behind a significant market into the UK.

With the development of wireless MEMS sensors and given the current commercial situation in which there is a wider range of non-standard acoustical instruments requiring calibration, much greater emphasis will be placed in the future on free-field calibration methods. Currently, reciprocity methods could be used but increasingly more versatile methods are needed to enable the magnitude and phase distribution of an acoustical quantity to be established at a point in a sound field. To meet this requirement, it is proposed that optical techniques are further developed, building on work pioneered in the 2001-2004 NMS Quantum Metrology Programme.

Theme structure

Setting aside the new scientific thrust areas, the overall proposed programme has the following six Themes:

- Standards for airborne and audiological acoustics
- Standards for underwater acoustics
- Standards for medical and industrial ultrasonics
- Acoustical standards research
- Knowledge transfer
- Programme management and development.

The main technical themes will provide the primary standards for realising the pascal in air and water over the industrially relevant frequency ranges. The outputs of these themes will provide the traceable calibrations for the UK, either through UKAS-accredited laboratories or directly from NPL.

Collaborations

Major challenges for the NMS Acoustical Metrology Programme are the growing demands for acoustical measurement of one sort or another. To address this, methods have been sought to enable greater delivery through collaborations. For example, in areas where there is a need to develop leading edge science, collaborations are being established with other organisations. In some cases, this involves the alignment of R&D activities with academia where it adds value to the NMS aims. In cases, where the output is directly relevant to industry, industrial co-funding is being sought to provide greater delivery.

Knowledge transfer

Dissemination of acoustical measurement practice is directly relevant to industry and all end users. Partnership with groups to deliver simple guidance on measurement issues across all areas will be sought. The already encouraging growth in the external use of the NPL Acoustics web pages will be enhanced by increased use of the web to promote good practice and to provide reference data. Opportunities will also be sought to collaborate with UK groups and other NMIs in the delivery of acoustical measurements and a study will be undertaken to look at ways of improving dissemination to UK plc, including devolution at both national and international levels.

CONTENTS

1. The National Measurement System

The National Measurement System (NMS) is the UK's national infrastructure of laboratories delivering world-class measurement science and technology, providing traceable and increasingly accurate standards of measurement for use in trade, industry, academia and government.

The NMS supports innovation in industry generally by enabling the benefits of new products and processes to be measured, and specifically, by stimulating new product development, improved process and quality control. Measurement also underpins a wide range of public goods including consumer protection (legal metrology), forensic science, environmental controls, safe medical treatment and food safety regulation, as well as the technical standards that ensure barrier-free trade.

The DTI is responsible for government programmes for the NMS and for policy on measurement standards. It is also responsible for:

- Management of the contract with NPL Management Ltd (NPLML) for the effective operation of the National Physical Laboratory (NPL)
- Management of the Teddington estate including the development of new laboratory promises under a PFI scheme.

2. Introduction to the Acoustical Metrology Programme

2.1 Background

The NMS forms the framework within which organisations such as the National Physical Laboratory establish primary standards of measurement of physical quantities, thereby enabling practical measurements to be made throughout the UK in industry, commerce, science, education, services and the home to be demonstrably traceable to the primary standards. As such it is a vital means of communication for all areas of society where meaningful measurements must be made and quantities understood.

The overall aim of NMS programmes is to maintain and develop a national infrastructure to ensure that measurement in the UK is valid, fit for purpose, consistent and internationally recognised. This infrastructure exists primarily to promote the UK's economic competitiveness and support regulatory needs.

The Acoustical Metrology Programme is one of the three-year programmes of work for which the NMS acts on behalf of the DTI and a wide range of beneficiaries. These programmes are required to provide an effective, competitive and comprehensive measurement infrastructure to:

- facilitate free trade
- benefit the competitiveness of UK industry
- meet statutory and regulatory obligations.

This document describes the proposed National Measurement System programme for Acoustical Metrology for the period October 2004 to September 2007 inclusive. It outlines the role of acoustical measurement standards in the UK, and describes the proposed programme, themes, projects and sub-projects. The proposed programme has been formulated on behalf of the National Measurement System Directorate by the National Physical Laboratory (NPL).

2.2 Objectives and scope of the programme

The Acoustical Metrology Programme covers the provision and development of measurement standards for sound - in air, water and water-like media - and the development of standardised methods of measurement for sound, noise and ultrasound to meet identified UK private and public sector needs.

The objectives of the programme are:

- to provide and develop national measurement standards in the field of acoustics, noise, underwater acoustics and ultrasonics, at a level consistent with the current and future needs of UK industry, national and local government and the health service, and make them accessible to customers in as practical and economic a form as possible

- to ensure that UK measurement standards in acoustics are harmonised with those of the UK's trading partners, through comparisons and collaborative research leading to mutual recognition

- to develop innovative new methods of measurement for sound, noise and ultrasound to meet identified UK private and public sector needs, and promote international standardisation of these methods to ensure consistency in practical measurements, especially where these are used for regulatory or 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 acoustical measurements.

2.3 Method of formulation

At the start of the programme formulation process, the DTI contracted Scientific Generics to carry out a comprehensive consultation study and produce a "Trends and Drivers" report to provide a policy steer. This report was one of the inputs to an Orientation Meeting held on 26 June 2003, organised by the DTI, to discuss the direction for the programme formulation process. Key output of this meeting, attended by some 45 participants, was a set of topics taken forward to the next stage of the formulation process.

Formulation then moved on to a wider level of consultation involving NPL's extensive links with end users of acoustical measurement standards in UK industry, national and local government and the health service. Consultation included:

- Customers and potential customers for NPL's measurement services (through meetings and site visits);
- Statistics on the demand for NPL services, and relevant trends in UKAS-accredited laboratory services;
- Policy statements of the UK government and European Commission on the control of noise, and of international organisations (IEC, ISO, CEN, OIML) concerned with specification standards in acoustics and ultrasonics;
- Impending changes to national and EU legislation on noise & vibration, and medical instrumentation;
- Discussions concerning future international measurement comparisons organised under the auspices of CIPM/CCAUV and EUROMET.

However, the main forums for brainstorming, discussing and distilling proposals for the new programme were five Thematic Group Meetings and two Satellite Meetings held in Autumn 2003. The Thematic Group Meetings were:

- "Noise" held at National Engineering Laboratory, East Kilbride on 2 September 2003
- "Medical and Industrial Ultrasonics" held at Huntleigh Healthcare, Luton, on 10 September 2003
- "Underwater Acoustics" held at NPL on 18 September 2003

- "Acoustical Instruments" held at NPL on 23 September 2003
- "Acoustic Emission" held at Lloyd's Register of Shipping, London, on 30 September 2003

and the two Satellite Meetings were:

- "Noise Emission - Machinery Noise" held at NPL on 21 October 2003
- "Noise Immission – Environmental Noise" held at NPL on 22 October 2003.

For each meeting, participants had received a compilation of topics and issues, generated by either the outputs of the Scientific Generics Report, the Orientation Meeting, consultations with experts, or NPL. At the meetings, key issues addressed were:

- what is needed to be done?
- drivers/justification
- identification of the role of the NMS
- collaborations
- priorities.

Features of these consultation processes were that it was clear that the main drivers for the formulation process should be meeting short and long-term needs through:

- seeking collaborations/co-funding to increase the level of resource devoted to delivering the programme
- establishing new long-term science in critical areas such as airborne noise measurement
- reducing the burden of the provision of standards.

Following the Thematic Group phase, the consultation process moved on to the presentation of a Public Release version of the programme in January 2004. Some 17 sets of comments were received from individuals and organisations which almost exclusively were supportive of specific aspects of the programme. The final stage in the process involved a prioritisation process involving the MAC Working Group, aimed at reducing the size of the programme by about 20%.

2.4 Collaborations and co-funding

In developing new measurement research areas to meet changing needs, a number of topics identified during the programme formulation were considered by the attendees of the meetings as being suitable for collaborative projects. Initially, some 13 sub-projects were identified by academic partners as being suitable for possible Research Council submissions. Furthermore, some 70 sub-projects were identified as having interested Third Parties from industrial companies, medical physics departments, environmental health officers to individual consultants etc.

Many of these projects have now developed further and seven EPSRC submissions are at various stages of development, all expected to be submitted by July 2004. In the main, the objective here is to establish projects that between them add resource to project delivery. However, as far as possible the aim is that the NMS and Research Council aspects of the proposed work are not mutually dependent, but mutually beneficial.

During programme formulation, a number of project areas arose too late to be included in the programme consultation process. Furthermore, contacts with other NMS Programme Managers and individuals have led to the compilation of a table of areas of mutual interest, which is given in Annex A. The intention is that these topics will be reviewed with experts from those other programmes during the three-year Acoustics Programme and collaborative projects between the programmes may be proposed for inclusion in the two programmes when opportunities arise.

2.5 Programme structure

More details about the structure and contents of the proposed new programme are given in Section 4, however the main conclusion from the initial consultation was that the programme should contain the following six Themes:

- **Standards for airborne and audiological acoustics**
- **Standards for underwater acoustics**
- **Standards for medical and industrial ultrasonics**
- **Acoustical standards research**
- **Knowledge transfer**
- **Programme management and development**

2.6 Long-term science - New vision for airborne sound measuring instruments and standards

The main drivers for measurement standards for airborne sound are emission measurements (machinery noise), immission measurements (environmental noise) and audiometric measurements. Some of the modern challenges in these areas are:

- measurements in complex machinery environments
- sampling the sound field from machines with increased spatial resolution
- accounting for environmental influences during noise immission measurements
- making reliable measurements in rooms (dwellings), especially at low frequency
- in-ear acoustic measurements
- increased sophistication of cheap measuring instruments
- use and calibration of non-standard microphones.

These challenges lead to uncertainties, often lack of reproducibility, and measurement problems in the 'real world' that are often at the level of many decibels. This contrasts with current acoustical metrology that has developed to a level of sophistication such that high calibre measuring instruments are available backed by international specification standards that are highly developed and between them are capable of giving results to less than a decibel. Whilst these low uncertainties can be realised in many 'well-behaved' measurement situations, increasingly the measurement challenges are the dominant limiting factors in industrial and environmental noise measurements. Furthermore, the challenges of cheap measuring instruments, the cost of employing skilled personnel, etc., are increasing pressures to consider alternative technologies.

To address this crucially important issue, it is proposed:

- to begin to address today's major noise measurement challenges through the development of a new generation of acoustical measuring instruments
- to base the vision on silicon MEMS technologies and wireless communications
- to base future calibration methods on free-field optical techniques (pioneered through the DTI Quantum Metrology Programme, Project 3.6).

A new generation of acoustical measuring instruments would be developed that are physically small (initially 'matchbox' sized but ultimately with dimensions about 10-15 mm) and based on a silicon acoustic sensor (MEMS) integrated with on-chip signal processing capability. By combining this with wireless communication to provide remote multi-channel operation, cheap, robust and easy to use measuring instruments could be developed. Once proof-of-principle has been established, *Second generation* devices with additional sensing of particle velocity and other parameters, such as temperature, atmospheric pressure, wind speed, etc., should also be possible. Once these are developed with a proven performance capability for acoustic measurement, this would provide a quantum jump in versatility and measurement capability for airborne sound.

Of importance is that the proposed programme will be based on UK developments. The concept is to develop a new generation of measuring instruments that will be revolutionary and unique. The programme will therefore be facilitating the development of a new disruptive technology that will enable the shifting of the knowledge base behind a major new market into the UK. An important factor here is that these instruments will have greater market potential because they will provide the user with opportunities for making more measurements than previously possible simply because the user will be able to afford more instruments because they will be cheap. The user community will therefore be able to deploy more instruments and achieve greater output.

More details about how these sensors might be used are given in Section 4.4. However, consider the benefits for machinery noise measurement. A large number of small sensors could be deployed around a machine to provide greater spatial sampling. One might envisage space-frame panels of sensors being used to simplify deployment. *Second generation* sensors able to measure true intensity would allow sound power to be determined in complex environments. This type of measurement capability would greatly simplify and enhance machinery noise measurement and diagnosis.

Projects 4.2 and 4.3 in Theme 4 (Acoustical Standards Research) are the proposed first stages in the process of realising this vision. Project 4.2 deals with the application of optics to acoustical calibration and builds on the current Quantum Metrology Programme Project 3.6. Project 4.3 represents a major whole new initiative devoted to the research and development necessary to start a process of developing the proposed new generation MEMS-based acoustical measuring instruments for airborne sound. This is expected to be a collaborative project with industry and academia, in both cases building on existing UK capability.

It is recognised that the development of a new generation of measuring instrumentation is challenging. However, all the new developments must meet the requirements of the future user. Hence, within Projects 4.4 and 4.5, which deal with noise measurement, the aim is that these will establish limitations of existing measuring methods, limitations that will then feed through to the research and development of the new generation instruments by highlighting specific measurement problems that can be taken account in the specification and targets set in the new MEMS projects.

Just one example where the vision outlined here is consistent with and recognised by the wider acoustics community is that promoted through the CALM network, an EC funded project to establish a vision for future research to reduce environmental noise levels, which states that strategically.... "*it is important to provide support for the development of new technologies and solutions for the reduction of noise emission to an extent which cannot be achieved by existing technologies, but which is required to comply with future regulations and requirements*".

The economic importance of this work can simply be judged from 1996 European Commission’s Green paper 'Fair and Efficient Pricing in Transport' where the external costs of noise to society especially transport noise were estimated to be in the range from 0.2% to 2% of GDP. The Commission used the lower estimate of 0.2% of GDP which represents an annual cost to society of over 12 billion ecu. With noise being such a high cost to society, reliable measurement of noise is essential if noise is to be reduced. The financial return for tackling and solving the measurement challenges identified above will therefore be substantial.

As already indicated, the vision of a new generation of acoustical measuring instruments for airborne sound will revolutionise acoustical metrology. Whilst it should be possible to produce prototype devices and refine the measuring instruments over the next few programme cycles, once devices are proven, the challenge will be to take these forward commercially and to introduce them into the wider acoustics community, and within say twenty years to achieve a whole new acoustical measurement infrastructure, and with UK-based instrument industry.

3. Role of acoustics in UK society

The value of the NMS as a whole can be seen from a recent independent survey of users of the NMS by The Precise Group Ltd. They found that companies which are users of the NMS have increased profits following steps taken to improve their measurement processes during 2003.

Measurements of acoustical quantities are made very widely, by companies in manufacturing and service industries, authorities responsible for occupational and environmental health, hospitals and clinics, and by defence services, for many different applications. Examples include the noise emitted by sources such as aircraft and industrial machinery, the noise exposures of workers in their occupational environment and the general public where they live, individual persons' hearing sensitivity, the ultrasonic sound energy produced by medical therapeutic and diagnostic equipment and by industrial devices such as ultrasonic cleaning baths, and the sound fields radiated or received by underwater acoustical systems. The purposes of the measurements include the collection of information for product specifications and contracts, demonstration of compliance with regulations, access to markets, machinery design and technology development, assessment of public nuisance, comparison with safe exposure limits, ensuring accurate diagnosis and effective therapy, and enabling accurate underwater positioning, mapping and detection. Measurements of sound are made in both air and water, and the frequencies covered extend from below the lower frequency limit for human hearing of about 20 Hz, through the audible range to beyond 20 kHz, and in the case of ultrasonic equipment to frequencies of tens of megahertz.

3.1 Airborne sound, noise and hearing

The broad areas of technical application are noise emission by sources, noise exposure of people, and measurement of hearing.

Noise is recognised by statute to represent both a cause of nuisance and a hazard to hearing. There is an extensive body of regulations in place in the UK to control noise and to limit its emission from specific sources such as aircraft, motor vehicles, and industrial and domestic machinery, many of which enforce EC Directives. In addition, there are a large number of British and international specification standards defining methods of noise measurement and testing and also the performance and methods of calibration of acoustical measuring instruments. Extending beyond statutory requirements, noise now features prominently in many product specifications and commercial contractual provisions, and in environmental/urban planning, design and monitoring. Noise is measured using a sound level meter (or more sophisticated noise analysis system) that utilises a microphone as a sensor and would normally be calibrated in the field using a sound calibrator. There are three main UK manufacturers of sound level meters and it is estimated that 4,000 to 5,000 meters are sold in the UK each year.

Dealing with the first broad area of technical application, noise emission measurements are now a common requirement for UK industry. As an indication of noise emission measurement practice;

- All civil aircraft types, including helicopters, business and leisure aircraft have to be type certificated for noise;
- Road vehicles and motorcycles are also subject to type noise approval, in line with EC Directives, before being allowed to enter the market;
- A wide range of construction plant and equipment has to be type noise certificated and meet noise limits given in EC Directives;
- The EC Machinery Directive requires manufacturers of all types of industrial machinery to measure and state the sound pressure level at the position of the operator, and in some cases the emitted sound power level.

Regulatory focus over the past 20 years has quite correctly tended to concentrate on the reduction of noise emission by sources, such as to both reduce the noise exposure of workers and limit industrial noise emitted into the environment. For the machinery industry there are a number of Directives in place, which require manufacturers to measure and declare the noise emission levels of machines

Directive 98/37/EC (http://www.dti.gov.uk/strd/machiner.html) is the most broad ranging of these, covering a wide range of machinery types, and requiring manufacturers to give information on the A-weighted sound power level if the sound pressure level at the work station of the machine exceeds 85 dB. The information is needed before the CE mark can be affixed to the machine indicating that it meets the essential health and safety requirements of the Directive, so it is a prerequisite for placing the machine on the market. Total UK sales of the wide range of machinery covered by the Directive are at least £15,000 m per annum, while total exports are valued at more than £20,000 m. Most recently, the machinery industry has had to comply with Directive 2000/14/EC (http://www.dti.gov.uk/strd/outdoors.html), which deals with noise emitted by machinery used outdoors. Similarly, this Directive requires manufacturers to measure or have measured the sound power level of 57 categories of equipment, 22 of which have to meet limits. It further requires that labels be affixed to each item of equipment showing the guaranteed sound power level and that declarations of conformity be issued. Unlike previous Directives, this Directive permits the manufacturer to carry out noise tests under the scrutiny of a Notified Body. In the UK, nine Notified Bodies have been appointed by DTI. A Compliance Cost Assessment for DTI carried out in 1997 estimates that in the UK, 250 companies manufacture machines covered by the Directive and the total cost to these companies of the activities in the Directive is estimated at £380 m, over the anticipated eight-year duration of the Directive.

Separately from these, the earlier Directive 86/594/EEC (http://www.dti.gov.uk/strd/household.html) made provision for labelling household appliances with their sound power level on a voluntary basis, and this was followed by Directive 92/75/EEC, which made the noise labelling mandatory. It is noted that although application of the UK Regulations remains voluntary, mandatory application may be required by other EC Member States, thus obligating UK manufacturers to make the necessary measurements to ensure access to the European market.

The second broad area of application for measurements of airborne sound is measuring and controlling noise exposure. The status of how noise exposure is dealt with throughout Europe was reviewed in the EC Green Paper on Future Noise Policy (1996), and resulted in a proposed framework for action to substantially reduce environmental noise. Elements of impact include up to 170 million citizens of the EU were said to be living in areas where the noise levels were such as to cause serious annoyance during daytime. People reporting noise-induced annoyance experience a reduced quality of life and this is a reality for at least 25% of the population across the EU. Furthermore between 5% and 15% of the EU population suffer serious noise induced sleep disturbance.

Directive 2002/49/EC Assessment and Management of Environmental Noise was implemented to drive the vision, and to date has resulted in considerable activity, primarily focussed on the production of strategic noise maps for all major "agglomerations", where so far in the UK, £13 m has been allocated. These strategic activities place additional burdens on UK Local Authorities required to produce noise maps. In constructing the maps there are questions about quality control of prediction software. When the completed maps enter into services as decision making tools there are likely to be validatory demands prior to reduction and preservation Action Plans. The Commission estimate the cost of implementation of the proposal as 30 to 40 million ecu annually.

Remaining on a policy level, but at more localised scale, the Mayor's Draft London Ambient Noise Strategy recently identified noise as a major environmental concern. It accepted that diagnosing the source of annoyance, and designing appropriate solutions to noise problems can be difficult and that control technologies are often specific to the particular industry. Furthermore, it accepted that impulsivity, intermittency and tonality can be particularly disturbing features of industrial noise. Clearly, these observations support the need for objective estimates of Sound Quality.

Alongside strategic activities, local authorities take responsibility for the control of environmental noise, particularly in the areas of environmental health, planning and traffic noise from highways. Local authorities receive tens of thousands of complaints each year concerning noise, many of which are confirmed as statutory nuisances following investigation. Objective noise measurements are commonly required. Powers to deal with environmental noise are provided under the Environmental Protection Act

1990, Noise & Statutory Nuisance Act, and most recently the Noise Act 1996, which is intended principally to control night-time neighbour noise. Traceable measurements play an important evidential role.

It is estimated that UK industry spent £120m on environmental noise protection in the year 2001. Regarding industrial noise, Directive 96/61/EC concerning Integrated Pollution Prevention and Control (IPPC) sets out the general obligation of all installations covered by its Annex I to take all appropriate preventive measures against pollution - including noise - in particular through the application of best available techniques. Looking forward to 2003-2005, investment is likely to increase in order for companies to comply with increased legislative burdens, particularly the phasing in of the IPPC regulations.

There has been considerable interest in the EU to assigning monetary values to the adverse effects of noise. In the UK, and at present, the DETR does not regularly use monetary values of noise in the appraisal of transport schemes. Nevertheless the DETR has reviewed studies of external costs of noise and has come up with the following broad conclusions for the cost of road and air traffic noise in the home:

- £15-£30 per decibel per household per year (covering 4 studies)
- 0.02 –2.27% GDP (covering 15 studies).

Occupational noise exposure is controlled in the UK by the Noise at Work regulations, which implement Directive 86/188/EC. Noise levels of at least 85 dB(A) (the first action level under the regulations) are thought to be present at more than 80,000 workplaces throughout Britain. The HSE estimated that in 1994 about 845,000 workers were exposed to noise above this level. Under current legislation, 25.7% of firms provide audiometry in establishments with noise levels over 85 dB. Under the new Physical Agents (Noise) Directive published in the Official Journal of the European Union in 2003 (to be implemented by Member States by February 2006), an exposure limit value (taking account of any hearing protection) of 87 dB(A) will be fixed whilst upper and lower exposure action values (irrespective of protection) are 85 dB(A) and 80 dB(A) respectively. This means that employers will need to be geared up for providing health surveillance by working out how many will be exposed above 85 dB(A) and which employees may be susceptible to noise induced hearing loss down to 80 dB(A) through a risk assessment and advice from HSE. Employers will also need to put the systems in place for providing audiometric testing and recording/reviewing results.

Hearing loss has been a prescribed occupational disease eligible for compensation by the Department of Social Security (DSS) since 1974. In fact, deafness is the second most common disability in the society generally, affecting an estimated 9 million people, about one in seven of the population UK in total. Since hearing loss increases sharply with age, this is set to grow as the proportion of older people rises. However, it should not be inferred that hearing loss is predominantly a disability affecting aging people. In 2002, the Swedish Association of Hearing-Impaired People, published data indicating that 54% of hearing-impaired people in Sweden were under the age of 65. One reason is likely to be the increased level of noise in our environment, from both occupation and social origins. The proliferation of electronic accessories including the now widespread use of in-ear devices such as personal stereos and mobile phones, high powered entertainment systems, noisy cars and motorcycles, power tools etc. has led to the noisiest lifestyle of any generation so far. There is already evidence that this is having a significant effect on hearing. In the USA, 8% of people aged 30 were recently found to have a hearing impairment.

The cost of hearing impairment is both economic and social. In 1996, RNID prepared estimates of the number of people of working age with a hearing loss and found that in total, more than 6.5% of the population between the age of 16 and 60 were mildly to profoundly deaf. In 2000, the Better Hearing Institute in the USA published an estimate of the annual costs due to lost productivity, special education and medical care as a result of untreated hearing loss, and sets the amount at $56 billion per year ($216 per capita). A similar estimate for the EU predicted the amount to be €106 billion by the year 2005 (€260 per capita), not accounting for the recent enlargement. This figure corresponds to the costs of building five Channel tunnels a year between Britain and France.

The social consequences and impact on quality of life are perhaps even more significant. Reactions differ from person to person, but most hearing-impaired people suffer some social, psychological and physical problems as a result of their hearing loss. People who suffer from untreated hearing loss often find it extremely difficult to participate in social activities, even within their own family. Some common social problems for people with untreated hearing loss include

- Reduced social interaction and social activity
- Difficulty communicating
- Anxiety and frustration
- Diminished self-confidence

Studies in the US have shown a strong correlation between hearing and quality of life. A number of studies indicate that hearing-impaired people benefit socially and psychologically, and improve their quality of life when their hearing loss is treated with a properly fitted hearing aid. The benefits are well documented with surveys reporting a significant reversal of the negative effects listed above. For example, a survey conducted by Keppler-Konsumforschung in Germany of 580 hearing impaired people, indicated that 70% find that their enjoyment of everyday life improved after they were fitted with *digital* hearing aids. Another German study carried out by Simon Kucher & Partners confirm the results and further reported that more than half of their 614 respondents felt that the digital hearing aids helped restore their ability to communicate in a normal fashion.

About 2 million people in the UK have hearing aids, but only 1.4 million use them regularly. There are at least another 3 million people who do not have hearing aids but experience significant hearing difficulties in everyday life, and are likely to benefit from hearing aids. The problem of ineffective hearing aids and not reaching all that require them is being addressed by the Department of Health. An initiative launched in 2000 sets out to modernise hearing aid services in the UK and make the latest hearing aid technology available on the NHS. This programme is due to be completed in 2005 with the integration of all audiology services in England into the scheme. Speaking about this, the health minister John Hutton has said,

"*It is vital that the deaf and hard of hearing are provided with a modern service, using the best available technology*"

"*The modernised audiology service will be based on digital hearing technology which transforms the lives of people with hearing difficulties. Digital hearing aids offer an immensely better clarity of hearing, not possible with traditional aids. Research shows that digital aids offer patients a 40 per cent improvement in hearing and quality of life*."

"*To ensure this happens, we will be working with NHS Supplies, who as the world's biggest supplier of hearing aids, will need to make informed decisions about digital aids purchased for the NHS.*"

The basis for prescribing and fitting a hearing aid effectively (digital or otherwise) is the measurement of hearing thresholds using pure tone audiometry. Indeed, *everyone* is likely to have their hearing tested on a number of occasions during their lifetime, to monitor their hearing function generally and for diagnosing the onset of any hearing loss. This is only viable using a measurement procedure, since the onset of hearing loss is unlikely to be apparent subjectively. For this purpose there are in excess of 1,000 audiometers in use in the approximately 200 ENT departments in England and Wales. Many of these departments run hearing aid clinics, providing about ½ million hearing aids annually at a cost of approximately £25m (excluding staff costs). In addition, there is a substantial private sector provision of about 80,000 hearing aids annually from some 600 dispensers. Each hearing aid prescription requires at least one set of audiometric measurements.

While pure tone audiometry has traditionally been the basis for hearing measurement, other assessment methods are now finding a place along side this in routine clinical practice. Classed generally as objective audiometry, these methods rely on responses to an auditory stimulus elicited without a conscious action by the patient. Such methods include evoked response audiometry (ERA) that detects brain activity correlated with an acoustic stimulus, and otoacoustic emission (OAE) methods that detect acoustic signals emitted by from the ear as a by-product of a correctly functioning hearing mechanism. There are many other methods under investigation in various research institutes and hospitals, and the UK has been pioneering this field.

In fact, OAE is now widely used to assess the hearing function of newborn children in the UK, usually in the first few days after they are born and before they leave hospital. A number of centres around the UK are already set up to do this and the universal neonatal hearing screening programme aims to make this regular practice throughout England and Wales for *all* newborn children by 2005. Identification of hearing problems as early as possible enables children and their family to develop communication skills necessary for their successful development.

A further area of application of acoustical measurement is building/room acoustics. Building Regulations, Approved Document E, came into effect in July 2003 and addresses standards for sound insulation in homes and many other types of buildings. The requirements for testing are at least one set of tests for every ten buildings. Of technical concern is the concentration on low frequency performance and reverberation, which raises technical issues related to poor reproducibility of measurement, a major driver for the new initiatives described in 2.6 and 4.4.

3.2 Water-borne sound including ultrasonics

Here, the principal areas of application are underwater acoustics, and medical and industrial ultrasonics. In the case of underwater acoustics and industrial ultrasonics, the requirements for measurement spring from the need for quality assurance in product specification, design and manufacture. In the case of medical products, there is also a very important issue of safety.

The UK has long been a maritime nation. Today, offshore oil and gas are the principal source of our energy, marine transport is the dominant method for importing and exporting goods, naval activities are vital for the implementation of our defence policies, oceanographic studies deepen our understanding of man’s effect on the planet, and marine recreational and leisure activities continue to expand. Underwater acoustics plays a key role in all aspects of off-shore activities as it is the major means of transmitting and receiving information un water.

The UK is Europe’s leading producer of underwater acoustical systems, with some 20 UK companies involved in manufacturing sonar systems. The European *civil* market for underwater acoustical systems (“wet-end”) is estimated to be £170 m-£200 m per annum. Accurate measurement of system performance is important for ensuring unambiguous specification and acceptance testing.

The applications of underwater sound span positioning, communications, navigation, echo-sounding, sub-sea control, seismic measurements, water quality measurement, sonar, weapons systems, and tomographic measurements of ocean currents and temperature. Civil offshore activities are heavily dependent on underwater acoustic technology and recently published statistics on markets indicate growth.

In 2000, Douglas-Westwood Ltd estimated global marine market sectors of: Offshore oil and gas production $300 bn, shipping, $234 bn, naval expenditure $225 bn and research and development $19 bn. Some sectors such as Ocean Surveying are ‘Enabling’ sectors as they are vital to the major sectors (e.g. offshore oil and gas). More recently, Douglas-Westwood in their Ocean Survey Report 2004-2008 values the world market for <u>Ocean Survey</u> (for which acoustical systems are essential) at $2.5 bn in 2004 and forecasts it will continue its long-term growth trend to reach $2.8 bn in 2008. Future growth areas are in deep and ultradeep water offshore oil and gas markets, with the development of sub-sea processing and new technologies. These deep-water activities increasingly require the use of autonomous underwater vehicles (AUVs), where acoustic technology plays a key role in visualisation, and in their location and positioning. With strong growth in world energy demand, an average growth of 8% in subsea oil wells is predicted over the next five years. With the relatively poor performance of other technologies in the marine environment such as those based on electromagnetic transmission, acoustics is an essential enabling technology, playing a vital role in many aspects of the off-shore industries.

In the UK, the marine industries are of great economic importance; a major employer with some 350,000 people (compared with 297,000 in agriculture and 155,000 in aerospace). The Inter-Agency Committee on Marine Science and Technology (IACMST) has updated the results of an earlier analysis on the contribution of marine-related activities to the UK economy. Compared to the 1994-1995 estimates of £27.8 bn, the 1999-2000 figures show significant growth with the “value-added” contribution from the marine sector being estimated at £39 bn, or 4.9% of GDP, with the overall turnover of the sector estimated at £69 bn.

There has been a strong demand for new subsea telecommunication cables as the use of the internet grows internationally. The manufacture, surveying and laying of new cables is an industry for which the UK share has been estimated at £497 m per annum in 2000 (IACMST report, August 2002).

The Working Group on the Exploitation of Non-Living Marine Resources of the Marine Technology Foresight Panel and the Sensors and Sensor Systems Working Party of the Defence and Aerospace Sensors and Sensor Systems Foresight Panel identified technology development priorities in the field of underwater acoustics. These developments will all place greater demands on methods for evaluating acoustical performance through calibration and testing, especially over the range of operating temperatures and pressures experienced in the oceans. A Marine Foresight panel report (http://www.foresight.gov.uk/) confirmed that the UK is a maritime nation and most of its external trade is carried by ship. Marine activities make a very significant contribution to the UK's prosperity and quality of life.

Exposure of marine mammals to underwater man-made noise is an issue of growing concern as the effects of noise pollution in the ocean begin to be understood. Increasingly, an environmental impact assessment is being required before activities which may generate underwater acoustic noise may commence. The impact may be on marine life, divers, or on other users of acoustic equipment. To assess noise impact it is first necessary to have agreed methods of characterising the noise source. This issue is set to increase in importance in the future, with the likelihood of future regulations which will require underpinning by well-founded metrology and appropriate specification standards

According to Business Communications Company Inc., the USA ultrasonics technology market (defined as use of devices operating in the frequency range 20 kHz to 500 MHz) currently stands at $3.6 bn. This market is projected to have an average annual growth rate of 8.5%, and to reach $5.35 bn by 2008. The ultrasonics industry is comprised of the following major segments: ultrasonic transducers, high power industrial ultrasonics, low power industrial ultrasonics, and medical ultrasonics. Noticeable trends are: ultrasonic welding and joining is expected to grow at an annual rate of 7.7% through 2008, and medical ultrasonics is predicted to grow by 9.7% per annum.

Medical uses of ultrasound include foetal monitoring, diagnostic imaging, Doppler blood-flow studies, physiotherapy, the non-invasive destruction of kidney stones (lithotripsy) and also tissue ablation using high intensity focussed ultrasound. In all of these areas, the principle concern is the safe and effective use of this equipment. This is particularly true in the case of obstetric scanning, where the potentially sensitive developing foetus is exposed to ultrasonic energy. In line with the majority of the western world, virtually all pregnancies within the UK are the subject of at least one ultrasound examination. It is well established that at sufficiently high levels, ultrasound can cause damage to tissue through heating and cavitation, and that some modern types of diagnostic equipment generate acoustic pressures close to those which are considered to be hazardous. These exposure levels have also been the subject of an eight-fold increase over the last 12 years; a development which has been driven by a change in the US FDA Reporting requirements. A balance needs to be struck by clinical staff between potential hazard and the anticipated diagnostic benefit. An accurate knowledge of the acoustic pressures and powers generated, and consequent tissue heating, is therefore crucial for this assessment. Similarly, effective therapy and lithotripsy depend on well-characterised treatment systems.

The US Food and Drug Administration requires manufacturers to comply with acoustic output limits for specific clinical applications. Alternatively, manufacturers may choose to meet a higher limit provided that they give on-screen indications of thermal and non-thermal indices which are related to potential for tissue heating and cavitation, and which allow clinical staff to make a professional judgement. Compliance with US FDA regulations by UK manufacturers is essential for access to the US market, and now specification standards to support the EC Medical Devices Directive place similar requirements on manufacturers to declare acoustic output levels. However, in such a rapidly developing area of technology, it is essential that developments in measurement methods and standards keep pace, thereby ensuring the continuing efficacy and safety of this important medical modality.

Medical applications which harness the destructive capability of the ultrasonic fields continue to develop. Some thirty years ago, Extra Corporeal Shock Wave Lithotripsy (ESWL), was developed as means of destroying kidney stones and it is now used routinely. Today, the use of high intensity focused ultrasound (HIFU) for ablative surgical procedures deep in the body (for instance for the destruction of tumours) is undergoing rapid development worldwide and appears to have a strong future. Following successful clinical trials, a French system called 'Ablatherm' has been approved for use in France and Germany and is used routinely in nine centres with around 2,000 patients having been treated. Clinical use of HIFU is widespread in China and at least one of their manufacturers is now bringing equipment to Europe for clinical trials on liver lesions. One such system is now at the Churchill Hospital, Oxford.

Some other relevant statistics related to the range of uses of medical ultrasound are:

- Around 30 lithotripters, 2,500 ultrasonic scanners, 10,000 ultrasonic foetal heart-beat detectors and 20,000 ultrasound therapy units are in use in the UK;
- World-wide, it is estimated that there are 250,000 diagnostic ultrasound instruments and 250 million examinations per year;
- In the year 2000, the UK medical diagnostic ultrasound equipment market is estimated as 1,150 units, of value £100 m, representing a growth rate of 7.6%. The largest area is obstetrics and gynaecology, taking about 35% of new units;
- Use of ultrasound by General Practitioners is growing at a rate of 6.7% per annum;
- The total number of ultrasound scans undertaken in the NHS is over 4 million per annum;
- Nearly all pregnancies in the UK are subject to at least one screening test using ultrasound, and approximately 2 million obstetric ultrasound scans are undertaken in the NHS per annum;
- There are 60,000 hip-fractures per annum within the UK, costing the NHS £1 billion per year - of relevance to ultrasonic characterisation of osteoporetic bone;
- There are 10,000 hospital admissions per year for urinary stone disease, 85% of which are now treated by lithotripsy.

The UK has developed a world-wide reputation as a source of manufacturers of key measurement instrumentation within the water-borne sound area. A prime example of this lies in the membrane hydrophone, originally produced developed by Marconi, whose development revolutionised measurement capability within the area of ultrasonics. The membrane hydrophone has been pivotal in providing the gold-standard capability for absolute measurements of the key properties of medical ultrasonic fields. More recently, the technology has been taken on and further developed by the UK SME, Precision Acoustics, and they are rapidly developing into the leading supplier of hydrophones which may be regarded as the ‘gold standard’ of measurement. NMS funding through the Acoustical Metrology Programme, has played a seminal role in initially supporting the development of these hydrophones as reference measurement devices, but latterly providing calibration services. Similarly, UK medical equipment manufacturers have benefited from the NMS: a recent example lies in one of Europe’s leading manufacturers of foetal monitoring equipment, who have commissioned an end-of-line acoustic output monitoring system for characterising the acoustic output of every medical transducer they produce. This capability has been made possible through the NMS funding, and the knowledge and experience in ultrasonic metrology which this has underpinned.

Within the area of industrial ultrasonics, high-power applications of sound include cleaning, materials processing and sonochemistry. The world-wide ultrasonic cleaning equipment market is estimated to be £1.5 bn and in the USA it is growing at 6.4% per annum. In the UK, there are 20 manufacturers of ultrasonic cleaning equipment with an annual turnover of £40 m. Applications of high power ultrasound are continuing to proliferate, a prime example lying in its use within the waste-water treatment area where novel devices generating acoustic powers in the range of 10 – 100 kW are being used to breakdown sewage sludge. There is considerable interest in further developing this technology, and major capital equipment of value £100 - £200 k is starting to be implemented within plants, driven by the operational benefits accruing from improved sludge de-watering, gas production and solids reduction. Both this, and the wider development and application of high power ultrasound demands reproducible measurements, both due to the need to successfully replicate and scale-up industrial processes from pilot-plant level, but also in order to monitor and control processes effectively. The action of the ultrasound is exceedingly complex but cavitation is known to play a significant role in these processes. Several of the companies producing high power equipment which can be utilised within these applications are UK based. Progress over the last few years in industrial uses of high power ultrasound has increased with a wider range of applications leading to greater commercial investment opportunities. However, the lack of measuring devices for use in this hostile environment has been seen as a barrier to development.

Nondestructive testing (NDT) technologies are used in industry to help ensure the integrity and reliability of products being provided to end users. Overall, the field of NDT is in a mature state and plays a significant role in our manufacturing economy, playing a leading role in key industries. Core NDT technologies are evolving in important ways and are more and more user friendly. The applications in which NDT is used are also expanding rapidly. The potential market for nondestructive testing equipment continues to expand with emphasis on product quality, lean manufacturing, just-in-time inventory practices, and advances in nanomaterials and related manufacturing and testing. In 1999, Business Communications Company Inc. (BCC) predicted the USA NDT market would grow at 3.6% to reach $0.95 bn by 2004. This growth has been exceeded, and according to a recently updated report from BCC, the USA NDT testing equipment market currently stands at $1.4 bn, and is projected to have an average annual growth rate of 5.1% reaching $1.77 bn by 2008. Of the various technologies used in NDT, acoustic emission and ultrasonics have shown a consistent higher annual growth rate, typically about 6%.

4. Programme structure

The programme is comprised of six themes. There are three themes dealing with the main measurement standards, a fourth dealing with research, including the long-term research outlined in Section 2.6, a fifth covering cross-theme knowledge transfer, and a sixth on programme management.

The six themes are:

Theme 1: Standards for Airborne and Audiological Acoustics
This theme provides for the realisation of primary standards of sound pressure within and beyond the audible frequency range; the calibration and verification of microphones, sound calibrators, ear simulators, and digital hearing aids.

Theme 2: Standards for Underwater Acoustics
This theme covers standards for underwater acoustics, providing for: the realisation of primary standards of acoustic pressure at frequencies below 1 MHz; the calibration/testing of hydrophones, projectors and underwater acoustical systems; and including the calibration at hydrostatic pressures and temperatures corresponding to real ocean conditions.

Theme 3: Standards for Medical and Industrial Ultrasonics
This theme covers standards for medical and industrial ultrasonics, providing for: the realisation of standards of acoustic pressure and power at frequencies above 1 MHz; the calibration of hydrophones, ultrasonic power meters and measurements of the acoustic output of medical ultrasonic equipment; standardised measurements of tissue heating caused by medical ultrasound; and measurements of cavitation relevant to both medical and industrial ultrasonics.

Theme 4: Acoustical Standards Research
This theme covers acoustical standards research for acoustic emission, and both machinery and environmental noise. It also covers work on ‘sound quality’ and new innovative methods for noise measurement. Most importantly, this theme covers the application of optics to acoustical measurement and the proposed new initiative on the development of a new generation of acoustical measuring instruments.

Theme 5: Knowledge Transfer
This theme covers cross-theme knowledge transfer aimed to promote the take-up of the outputs of the programme, and the adoption of good measurement practice, and to provide technical support and advice to UK organisations and individuals undertaking acoustical measurements.

Theme 6: Programme Management and Development
This theme covers programme management and development, to manage the delivery of the programme and ensure that objectives are met within time and budget, and to assist the DTI in the formulation of a follow-on programme.

Figure 1 shows a pie chart of the breakdown of the proposed programme by theme and Figure 2 shows the balance of work in the programme by activity. It should be noted that the Knowledge Transfer Theme data given in Figure 1 refer to the cross-programme knowledge transfer activities whereas Figure 2 includes all knowledge transfer activities, i.e. including those within the themes.

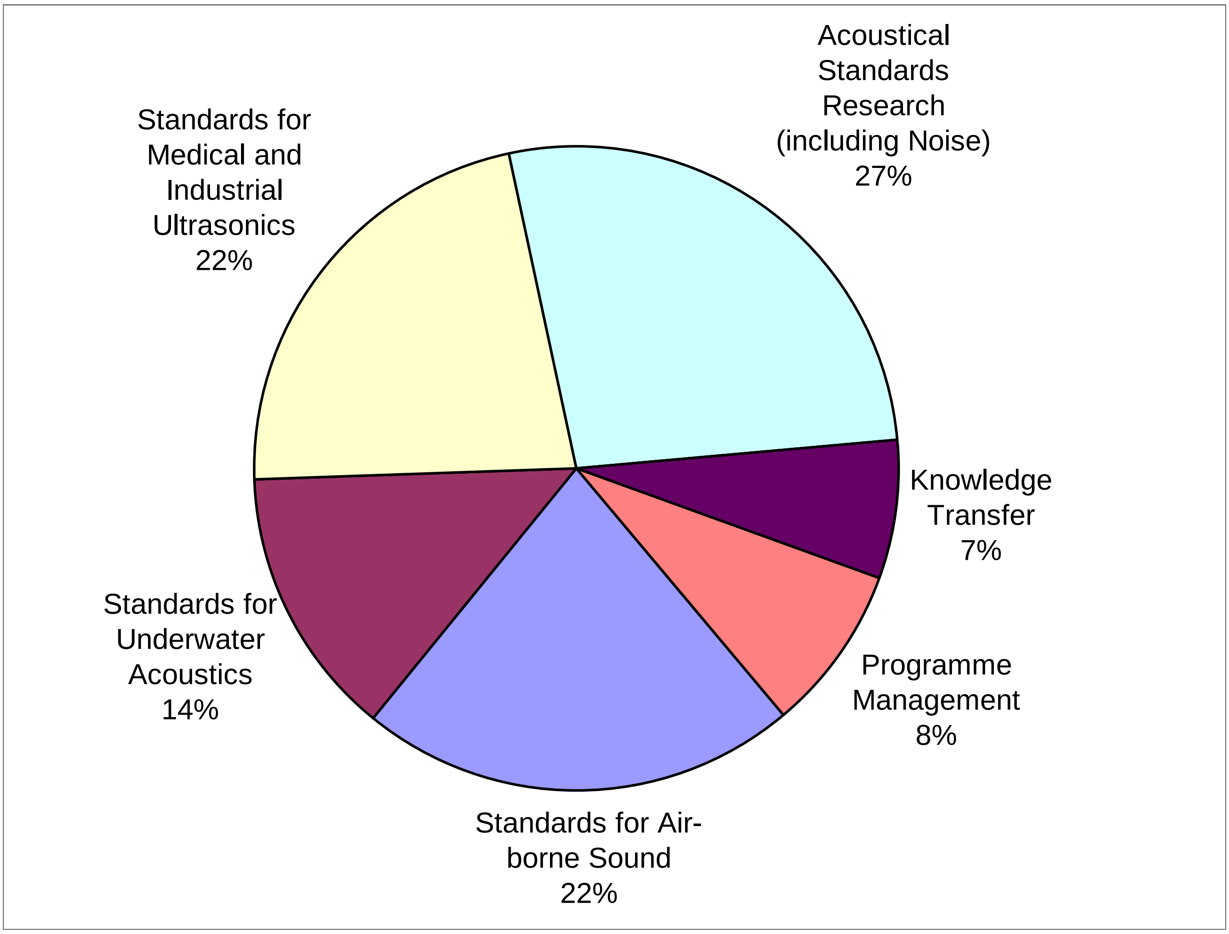


Figure 1: Balance of the proposed programme by Theme

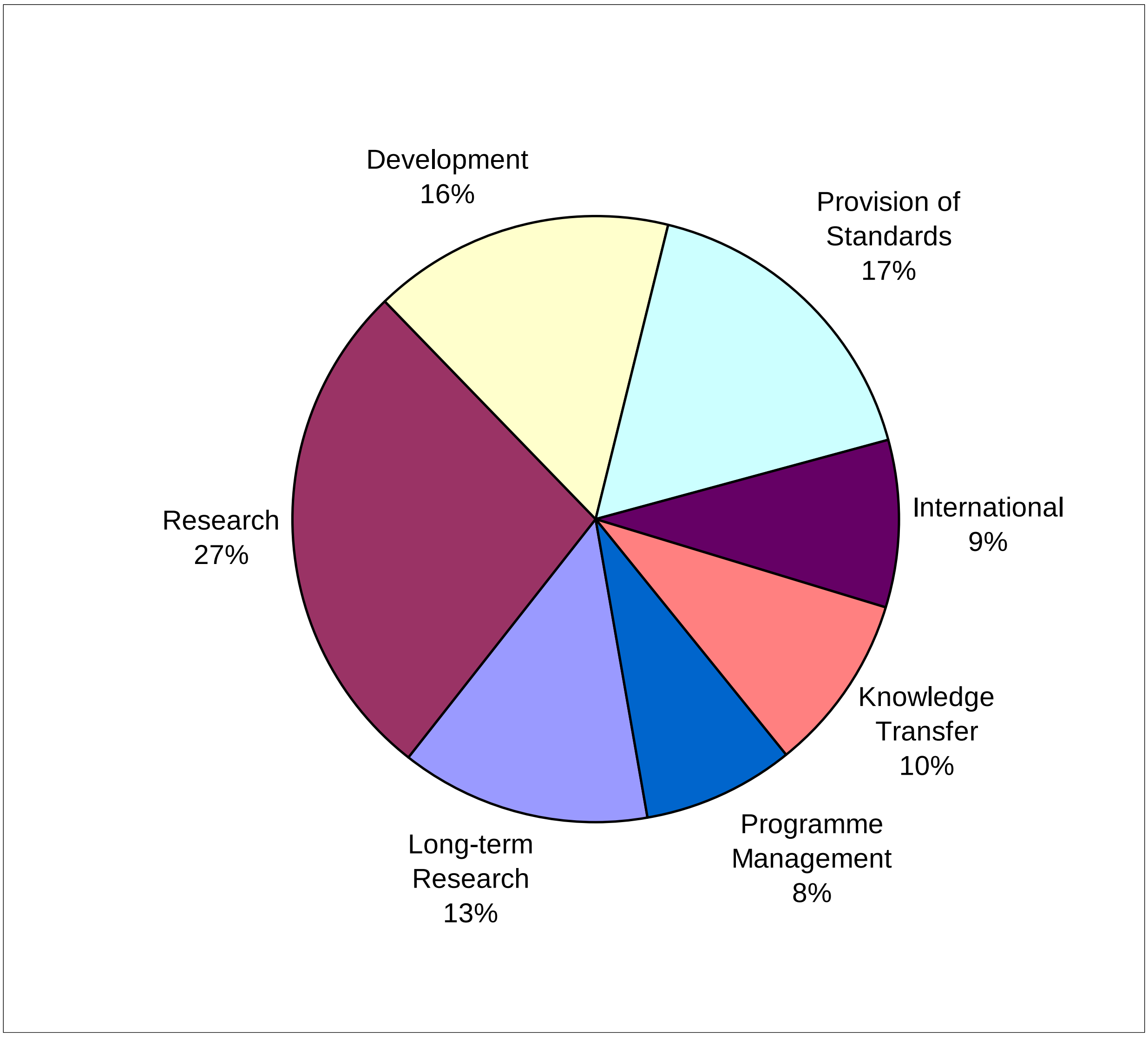


Figure 2: Balance of the proposed programme by Activity

The following sections of this document introduce the themes in more detail and describe the aims and rationale for each theme. Each theme has a small number of projects designed to address the overall programme requirements.

4.1 Theme 1: Standards for Airborne and Audiological Acoustics

Aims
The aims of this theme are:

- provision of primary standards for sound pressure in air, including the requirement to demonstrate equivalence of our standards with those of our trading partners
- dissemination of standards, largely achieved through the development, and where appropriate, delivery of specialised measurement services for the calibration of sound measuring instrumentation. These include calibration both for general purpose measurements and for specific applications having a widespread impact on the community
- addressing the need for instrumentation to comply with certain minimum performance requirements beyond the need to simply be calibrated. This is achieved through being involved in the development of international specification standards through IEC and OIML for example
- undertaking of research into new test methodologies to underpin calibration applications, an example of this is the qualification of free-field rooms.

Challenges in this theme include the development of simplified, low-cost calibration applications appropriate for lower-grade instruments in widespread use, and development of new ear simulator calibration methods to suit specific applications such as telephonometry and objective audiometry.

Background
Accurate and consistent measurements of airborne sound fulfil a wide range of regulatory, health, safety and commercial needs both within the UK and in support of international trade. Applications arise in the measurement of machinery and product noise (noise emission), environmental and workplace noise (noise immission), hearing protection, audiometry, and the quality control of acoustical devices.

The declaration and verification of noise emission values for all kinds of industrial machinery as presently required by European legislation presupposes the use of uniformly specified noise measuring instrumentation with tight tolerances. The control of noise immission requires instrumentation for measuring and assessing the noise exposure in places of work, public areas and private residences. The microphone systems and sound level meters used for these measurements incorporate response characteristics (i.e. frequency weightings and time weightings) which imitate, to a first approximation, the main responses of the human ear/brain system. The instruments are required to conform to standards agreed internationally by the International Electrotechnical Commission, and this provides a consistent basis for legislation, planning and preventative action.

The relevant IEC Standards on microphones, sound calibrators, sound level meters, audiometers and ear simulators are all under active development and revision to take account of advances in instrument technology and new calibration techniques. In the past in the UK, elements of international Standards/Recommendations on sound level meter verification have been incorporated into BS 7580 which has been used in support of the application of UK regulations on noise, in particular the Noise Act 1996. Recommendations on the pattern evaluation and verification of these instruments are prepared by the International Organization of Legal Metrology (OIML). The ongoing development of recommended formats for pattern evaluation reports will facilitate mutual recognition of test reports from different countries.

The calibration, specification and measurement of the performance of audiometers are traceable to primary standards for airborne sound through the calibration of secondary-standard devices known as ear simulators. The specification and measurement of the performance of hearing aids is based on the use of a calibrated acoustical input and measurement of the output using an ear simulator. The required characteristics of these ear simulators are specified by IEC standards.

EUROMET (a framework for co-operation between European national metrology laboratories) has an active programme of collaborative research and intercomparisons to develop, improve and validate European measurement standards in acoustics. The International Committee of Weights and Measures (CIPM) which oversees the fabric of the SI system, has set up a Consultative Committee (CCAUV) and has instigated a series of world-wide intercomparisons in acoustics. These allow activity in EUROMET, in particular intercomparisons, to be linked with other regional metrology groups in North America, Asia-Pacific, etc. It is important that the UK is actively involved in these developments.

Dissemination of measurement standards, from NPL to the end user, is through a variety of intermediaries. There are five UKAS-accredited calibration laboratories operating in the field of airborne acoustics (in addition to NPL, which is also UKAS-accredited). Major UK regional hospital centres and audiometer suppliers are also involved in dissemination for the measurement of hearing.

Rationale

Consultation with industry has affirmed the value of the NMS Acoustical Metrology Programme. Measurement standards continue to be vital for the wide range of applications throughout society and impinge on every individual. However, the consultation also highlighted changes in requirements that the programme aims to react to. In many applications calibration uncertainties, while appropriate for the highest grade of instrument, exceed a level befitting the grade of instrument that might be used. Consequently, the cost of such calibrations can exceed that of the instrument, so calibration is considered a financial burden, and in some cases it is cheaper to buy a new instrument (although this is no guarantee of performance), than have the existing one re-calibrated. In other applications, non-standard patterns of instruments are appearing, presenting further calibration challenges, since these also need to be accommodated, and once again, usually at low-cost. So while NPL needs to maintain primary standards for sound-in-air at the current levels of uncertainty, there is little pressure for improvement in this area. The driver for many of the new proposals comes from the need for lower-cost and faster calibration methods, suited to a wider variety of instrument designs, notwithstanding the degradation in uncertainty that is likely to accompany such methods. Methods need to be developed that can ultimately be transferred to UKAS laboratories in the future, enabling the technological developments to benefit the widest possible range of users. Another driver is for calibration methods suitable for specific applications such as ear simulator calibrations for oto-acoustic emission measurements to further support the measurement infrastructure within the UK health service.

Project 1.1 Primary measurement standards for sound in air

This project provides primary measurement standards appropriate for the wide range of acoustical measurements in air. These standards support sound pressure measurements for manufacturing and product QA, health, safety and hearing conservation, environment noise measurement and monitoring, and many other applications. Dissemination of the measurement standards is undertaken to a degree through NPL's own calibration services, all of which are underpinned by this project. However the support provided to UKAS laboratories by this project is also vital for their effective operation, enabling traceability to be spread far more widely than NPL could manage alone. The facilities require continual incremental development to keep pace with (or even drive) the understanding of the physics underlying the calibration process and embodied in specification standards. From time to time the facilities also need significant re-development to keep pace with changes in IT and to replace instrumentation before it becomes obsolete.

Project 1.2 Working standard microphones

Secondary calibration of working standard microphones can offer the most direct and cost-effective traceability path for sound-in-air measurements. However, there is a growing call for these methods to cover microphones having a non-standard pattern. Free-field calibration is currently heavily resource-dependent and requires specialised facilities. There is a need therefore to simplify the process and embody this in international standards, enabling secondary laboratories to develop such facilities. Associated with this is the requirement to qualify the performance of free-field rooms. However, microphone calibration is only one application where this is necessary. Others include sound power measurement of machines and hearing aid testing. An international standard is therefore required dedicated specifically to the testing of free-field rooms and enclosures, that can be referred to where other applications require such specifications.

Project 1.3 Sound level meters and calibrators

Sound level meters are the most commonly used instrument for sound-in-air measurements and the use of sound calibrators is the simplest way of providing traceability for such instruments. Consequently, calibration and periodic verification of the performance of these instruments is important for a vast number of users. It is therefore vital that the UK plays an active role in the specification standards in this field. Given the versatility in functionality of sound measuring systems (of which sound level meters can be considered a sub-set), and in the applications for which they are used, there is a need for best practice guidance on a number of aspects, such as verification of FFTs, checks on filters, or general frequency response measurement. Also advice is needed on the type of calibration and level of uncertainty appropriate for particular applications, such as sound power measurement. There is also a need to make recommendations on the level of calibration or verification appropriate for low-grade instruments, commensurate with their cost.

Project 1.4 Ear simulators and hearing aid testing

Measurements of hearing by pure tone audiometry are made traceable through the calibration of ear simulators. However, new techniques such as oto-acoustic emission and evoked response audiometry, while they may have been around for some time, are now seeing routine use in screening and diagnosis of hearing defects, and revolutionising hearing measurement on a national scale. The appropriateness of traditional methods of ear simulator calibration therefore needs to be reviewed and adapted to suit these newer applications. Indeed, the question of whether the ear simulators themselves, which pre-date the measurement methods to which they are being applied, are still fit-for-purpose needs to be addressed and the outcome embodied in IEC standards as appropriate. Going one step further, it may be time to consider the possibility of direct measurement of the in-ear sound pressure, thereby eliminating the need for ear simulators in the longer term.

Aside from audiometry, ear simulators are used in many other applications, including audio measurements for telecommunications. Bringing traceability to these measurements requires the development of new calibration methods and targeted knowledge transfer.

4.2 Theme 2: Standards for Underwater Acoustics

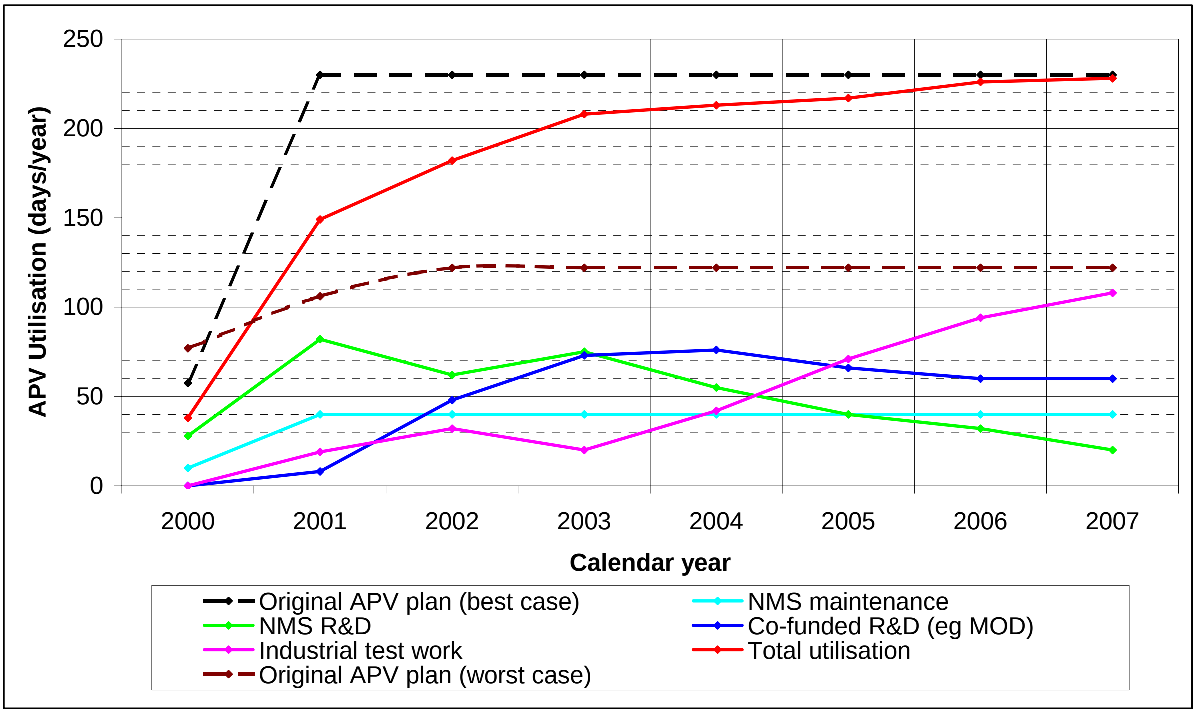
Aims
The aims of this theme are:
- provision of primary free-field measurements in the frequency range 1 kHz to 500 kHz for underwater acoustics
- provision of pressure calibration of hydrophones in the range from 20 Hz to 1 kHz
- dissemination of standards by use of state-of-the-art free-field test facilities consisting of both laboratory tank and open-water sites, and at simulated ocean conditions by use of the NPL Acoustic Pressure Vessel
- development of standards to meet evolving industry needs, for example in the assessment of noise radiated underwater by vehicles such as remotely operated vehicles.

Background
Progress made under previous NMS programmes has provided the UK with one of the most comprehensive and respected range of facilities for the provision of underwater acoustical standards worldwide. Indeed, NPL is the foremost NMI in this field. Primary standards for free-field calibrations at kilohertz frequencies are realised in laboratory tanks by the method of three-transducer spherical-wave reciprocity. Dissemination of free-field measurement standards in the UK from the primary standards held at NPL to the end-user occurs by customers directly using NPL measurement services or those of UKAS accredited laboratories (of which NPL is one). These primary standards have recently been extended to lower frequencies by use of a primary coupler-reciprocity technique, and an open-water calibration facility is available to for dissemination of standards to a wide user base.

The NPL Acoustic Pressure Vessel is a unique facility in Europe providing industry with a laboratory-based alternative to acoustic sea trials, which is an order of magnitude less expensive. This therefore provides industry with the opportunity to undertake new research and development which otherwise it could not afford. With the typical cost of sea-trials being of the order of £15,000 per day, the 2002-2003 utilisation figures for the pressure vessel represented a potential cost to industry of £455,000.

In addition, the APV provides a means of characterising transducers, arrays and materials under very controlled conditions, thus providing data which is simply not available by other means (for example, the determination of the dependence of transducer sensitivity on water temperature is perfectly practicable using the APV but not easily determined from sea-trials). With the APV, NPL provides the capability for free-field acoustic measurements at simulated depths down to 700 m (hydrostatic pressure up to 7 MPa) and at water temperatures between 2 °C and 35 °C.

APV Utilisation



The above plot shows the utilisation of the APV since commissioning in the autumn of the year 2000. Actual figures have been used for the years 2000 to 2003, with projections based on estimates derived from NPL business planning and from the likely content of future research programmes used for the remaining years. The plot shows the total utilisation, along with the utilisation for maintenance, industrial test work, NMS funded R&D and co-funded R&D undertaken with collaborative partners. This last category has shown higher levels than originally planned during the last year due to co-funded work such as the collaboration with QinetiQ Ltd on methods to acoustically characterise materials in the form of panels at simulated ocean conditions. For comparison, the original planned utilisation of the APV is also shown (best and worst cases).

Rationale

The field of underwater acoustics involves the generation, propagation and detection of sound in water. The main application areas in marine acoustics are the off-shore industry, defence and oceanographic science. UK industry is highly active in these areas, with the UK leading Europe in the production of underwater acoustical systems. Accurate measurement of these performance parameters is important for ensuring unambiguous specification and acceptance testing. Determining the acoustic performance requires traceable measurements to be made.

In the off-shore industry, remotely operated vehicles (ROVs) are used as sub-sea platforms for acoustic systems such as sonars and positioning transponders, enabling underwater visualisation and navigation. In the off-shore industry, there is a clear trend toward working in deeper water as the shallower coastal waters become more heavily harvested. This is setting new challenges as acoustic systems are required to work at greater depths and over greater ranges. The defence-related applications of underwater acoustics include anti-submarine warfare, with specific examples being active and passive sonar, mine-hunting, weapons guidance and counter measures. In the post cold-war environment, interest has moved away from deep cold-water applications toward applications in littoral waters, often in tropical climates. This provides its own challenges, one of which is ensuring the acoustic performance over a range of different water temperatures. The Acoustic Pressure Vessel is the means of providing these industries with the simulated ocean conditions test and calibration capability to address these issues.

In oceanographic science, acoustic methods are used for sea-bed mapping, bio-mass evaluation, ocean acoustic tomography, and the study of marine life. Deep ocean studies increasingly require the use of Autonomous Underwater Vehicles (AUVs) which are heavily dependent on acoustic systems. In shallow water, acoustic techniques are used in the study of sediment transport processes, important for assessment of coastal erosion and for protection of ports and harbours from mines (a potential terrorist threat which is taken ever more seriously). Improvement in the knowledge of hydrophone response and transducer performance in the presence of sediment will benefit users studying sediment properties for mine counter measures, environmental oceanography, seabed characterisation for the offshore construction and extractive industries, and for marine habitat mapping, a current core research objective of DEFRA.

The exposure of underwater mammals to man-made noise is another issue which is of growing concern as the effects of noise pollution in the ocean begin to be understood. Increasingly, an environmental impact assessment is being required before activities which may generate underwater acoustic noise may commence. The impact may be on marine life, divers, or on other users of acoustic equipment. To assess noise impact it is first necessary to have agreed methods of characterising the noise source. This issue is set to increase in importance in the future, with the possibility of future regulations which will require underpinning by well-founded metrology and appropriate specification standards

In the general area of acoustic field characterisation, the extension of the use of near-field measurement techniques offers the potential for characterisation of large high frequency transducers and arrays in laboratory tanks, with optical techniques offering long-term potential benefit. Many users of high frequency sonars report the need for new guidelines for their *in-situ* testing, in particular for the provision of standard targets with improved performance compared to those recommended in current standards (e.g. in IHO S44).

Of course, if the work within the NMS programme is to be effective, the results must be disseminated widely. This is partly achieved by measurement services, but there is still a need to raise awareness of measurement issues and promote best practice. This will be done through organising meetings and workshops (including in conjunction with bodies such as the IOA), and through direct industrial contact. The further development of technical guidance through application notes and web-guides will allow guidance to be provided on topics such as the technical specification of acoustic equipment, the correct use of terminology and units for acoustical quantities, and other issues that are raised in consultation with the user community.

The UK defence and off-shore industries operate in highly international markets, with UK-produced products often sold into other countries. Consequently, the acceptance of calibrations by other countries and the harmonisation of standards across international boundaries are of considerable importance. The plan is to continue to support work to compare the UK Standards with those of other countries for example under the auspices of EUROMET within Europe. The International Committee of Weights and Measures (CIPM) which oversees the SI system, has established a full Consultative Committee on Acoustics, Ultrasonics and Vibration (CCAUV) and the UK has led Key Comparisons in underwater acoustics and is in a good position to play a pivotal role in any future developments. In addition, work will continue within Technical Committee 87 of the International Electrotechnical Commission to revise specification standards as required.

Project 2.1 Underwater acoustical standards for hydrophone calibration

This work of this project underpins the provision and dissemination of standards in underwater acoustics in the frequency range 20 Hz to 500 kHz. The basis of free-field primary standards in the frequency range 1 kHz to 500 kHz is the calibration of laboratory-standard hydrophones by the three-transducer reciprocity method (IEC 60565), the coupler reciprocity technique being used for the calibration of standard hydrophones at frequencies from 20 Hz to 1 kHz. An improved understanding of the sources of error in these primary standards is vital if long-term improvements are to be made to the methodology.

These standards are disseminated either by direct calibration using the primary method, or by comparison with a calibrated reference hydrophone. NPL's free-field calibration service provides industry (including UKAS laboratories) with traceability to national standards. Free-field measurements are undertaken at ambient temperature and hydrostatic pressure in two open tanks, the largest being 5.5 m diameter and 5 m deep, and the smaller tank being 2 x 1.5 x 1.5 m deep. The tanks are equipped with precision positioning systems enabling accurate positioning and orientation of acoustic transducers under computer control enabling full characterisation to be undertaken of sophisticated sonar transducers. A calibration raft on an open-water site at Wraysbury reservoir is also routinely used to disseminate these standards widely to users in the frequency range 1 kHz to 350 kHz. This facility has the potential to be used for dissemination of standards at frequencies below 1 kHz.

The aim is to extend the capability of these services to provide the best match with industrial requirements possible, and to disseminate the results of the work to a wide audience by the most appropriate routes (direct measurement services, scientific papers, web-based information sheets, etc). Extending the capability will include:

- improved dissemination of the standards at frequencies less than 1 kHz where currently the provision is weakest
- establishment of a reference phase calibration capability for hydrophones so that the full response of the device can be determined
- developing an improved understanding of the sources of error in calibration
- harmonization of standards through appropriate comparison exercises.

Project 2.2 Underwater acoustical standards for acoustic field characterisation

This project incorporates a range of activities that are best described by the term acoustic field characterisation. This includes the extension of the use of near-field measurement techniques which can be applied to assessing large high frequency transducers and arrays in laboratory tanks, both to determine the far-field response and the acoustic distribution at the transducer surface, an excellent monitor of performance for individual array elements. The use of optical techniques may provide long-term benefit in this area.

As described above, underwater noise is of increasing importance both in its impact on marine life and its influence on the performance of other acoustic equipment in the vicinity (e.g. acoustic positioning systems which are crucial for accurate location and navigation in deep water). Before specification standards can be prepared, agreed methods of measuring the noise are needed which are rapid, flexible and sufficiently accurate. Such methods will enable financial savings to be made by industry since they will not require the use of expensive noise ranges.

Many users of high frequency sonars (including multi-beam echo-sounders) report the need for new guidelines for their *in-situ* testing, in particular for the provision of standard targets with improved performance compared to those recommended in current standards (e.g. in IHO S44).

Improvement in the knowledge of hydrophone response in the presence of sediment will benefit users in the oceanographic community studying sediment transport processes, important for studies of coastal erosion, and mine-hunting in shallow-water ports and harbours. In addition, studies of sediment are important for mine counter measures, environmental oceanography, seabed characterisation for the offshore construction and extractive industries, and for marine habitat mapping.

Finally, knowledge transfer provides an important part of this project. NPL has already provided technical guidance sheets and web-pages which have been highly valued by the user community. The further development of this dissemination route will allow guidance to be provided on additional topics such as the technical specification of acoustic equipment (not always clearly and unambiguously provided), the correct use of terminology and units for acoustical quantities (a source of considerable confusion in the past) and other issues that are raised in consultation with the user community.

Project 2.3 Underwater acoustical standards under simulated ocean conditions

This project provides standards for acoustic transducer testing and free field materials testing at simulated ocean conditions by use of the NPL APV, and disseminates those standards by operating measurement services. The results of the characterisation of commercial hydrophones will be disseminated to industry to act as guidance of the use of these devices.

The environmental conditions within the APV can be modified to simulate ocean depths down to 700 m (hydrostatic pressure from atmospheric to 7 MPa) and temperatures from 2 ^{o}C to 35 ^{o}C. With the APV, NPL provides a valuable national facility which is unique within Europe, a fact recognised by the UK underwater acoustic industry. This facility consolidates NPL’s already pre-eminent position as the world-leading NMI in underwater acoustics.

As noted earlier, the APV provides a cost-effective alternative to sea-trials which is an order of magnitude less expensive. To maximise savings to industry, it is therefore of considerable importance to be able to maximise the usefulness of the facility in terms of the technical capability. Novel methods will be investigated to increase the frequency range over which measurements may be made in the APV, with particular emphasis on the difficult low frequency range below a few kilohertz.

The materials used in underwater acoustics often have an important influence on the transducer performance, especially if the material properties vary with temperature and depth of immersion (for example for viscoeleastic materials). Methods of characterisation of these materials have been undertaken in the NPL APV, but there is a need to further extend the frequency range of the measurements down below the current limit of 5 kHz.

4.3 Theme 3: Standards for Medical and Industrial Ultrasonics

Aims

The aims of this theme are:

- provision of premier calibration and testing services for the area of ultrasonic metrology, providing traceability to both the industrial and hospital community
- undertaking of leading-edge metrological research and, through it, to develop, validate and exploit novel instrumentation to meet the requirements of the UK user community
- dissemination of the research through a variety of means: peer-reviewed publications; exposure of key results on the *www* and contributing to, and influencing, the development of international specification standards to the benefit of the UK
- promotion of the benefits and impact of the metrological take-up by the user community, through the coordination of targeted Knowledge Transfer events, including workshops addressing issues of measurement at the user level.

Background

Ultrasound is now the most common form of medical imaging (almost all pregnancies with the UK are the subject of at least one ultrasound imaging scan) and has a growing range of therapeutic uses. In obstetric applications in particular, where the developing foetus is exposed to an applied ultrasonic field, quality control of equipment and assessment of safety are paramount. Hydrophones, used for determining acoustic pressure, and radiation force balances, used for measuring acoustic output power, remain pivotal to these measurements. Over the years, UK companies, some of them SME's, have been at the forefront in terms of designing and manufacturing high quality measurement devices. Through NMS funding, the measurement infrastructure has been established providing a range of industrial and hospital users with the ability to undertake traceable, absolute measurements of key acoustical quantities in order to meet the requirements of international safety and performance standards. Medical ultrasonic applications, both diagnostic and surgical, continue to proliferate from an innovative UK community. With the need to meet the exacting measurement requirements posed by this emerging equipment, there is a requirement for new measurement techniques to be developed and for existing capabilities to be extended to ensure safe, effective and optimised application of medical technology.

High power ultrasound is used extensively throughout industry within a variety of applications from ultrasonic cleaning and sonochemical processing to ultrasonic welding. In the former two applications, acoustic cavitation is the agent responsible for physical and chemical changes generated within a medium, and there has been a long-standing need to develop standardised methods of measurement for both cavitation, and ultrasonic cleaning itself. Establishing this capability will allow the harnessing of the processing capability provided by high power ultrasound and enable difficult issues, such as industrial scale-up, to be addressed. It will also allow processes to be optimized, ensuring energy savings, and equipment designs to be refined. The improved understanding of cavitation dynamics and measurement will also impact on medical applications, where (mechanical) cavitation is considered an important potential source of hazard in diagnostic and surgical applications. Cavitation may be especially important in newer applications, where contrast agents are being used to improve image quality and to deliver therapeutic treatment.

Rationale

The drivers for traceable measurements of ultrasonic fields originate from patient safety (QoL), performance and access to markets. Although medical ultrasound has an excellent safety record, it is well established that the acoustic output levels generated by diagnostic ultrasound systems are high enough to generate significant temperature rises within clinical model (Thermal Test Object) systems. Work at NPL has indicated that, when bone is positioned within the acoustic beam, temperature rises in excess of 8°C can be generated by some systems. Within the therapy and surgical areas, reliable assessments of the ultrasonic exposure parameters are required to ensure optimised, safe and effective treatment, especially in emerging areas such as the use of High Intensity Focussed Ultrasound (HIFU) fields to destroy tumours. For UK manufacturers of medical ultrasonic equipment, access to measurement capability is essential for ensuring compliance with US FDA regulations, providing access to markets, and to the specification standards supporting the EC Medical Devices Directive, leading to CE marking. For a number of industrial sectors, developing a reliable and validated measurement capability will result in a better fundamental understanding of the processes taking place, leading to improved monitoring, control and optimisation. Industrial areas impacted by this Theme are as follows:-

- product manufacture e.g. medical ultrasound systems; specialist measurement instrumentation; ultrasonic cleaning vessels and high power sonochemical systems;
- materials processing e.g. pharmaceuticals; food and beverage; chemical and petrochemical; waste remediation.

Project 3.1 Ultrasonic pressure standards

The NMS primary standard for hydrophone calibration, a laser interferometer, will continue to be provided, and in response to an increasing industrial demand, the feasibility of extending its operating frequency range up to 100 MHz will be investigated. New hydrophone calibration services will be developed to keep pace with the continued development of the membrane hydrophone as reference wide band-width measurement devices. A new calibration service will be established providing higher frequency calibrations up to at least 40 MHz. A feasibility study will be completed to establish the upper working frequency range of the primary standard laser interferometer, in response to a growing need to develop such a measurements capability.Medium and long-term provision of Measurement Services will be assured through detailed evaluation and commissioning of hydrophones for use as replacement devices for the existing, ageing and non-replaceable, Marconi gold-standard hydrophones.

Project 3.2 Ultrasonic power standards

Services for hospitals and industry, relating to calibration of radiation force balances for determining ultrasonic output power, will continue to be provided and extended to include power determination at human body temperature. These services will be improved through the commissioning of an ultrasound therapy-level Portable Power Standard which will be made available to UK manufacturers and hospitals for use as a QA tool. Further theoretical and experimental evaluation of a novel (solid-state) pyroelectric-based technique for monitoring and determining ultrasound power will be undertaken. To address the needs of emerging medical ultrasound technologies, collaborative projects will be established with hospitals and academia for the development of new underpinning measurement techniques. This includes the development of standardised techniques for determining the essential properties of HIFU fields used within cancer therapy, and the extension of ultrasonic power measurement capability from the current upper limit of 20 W to at least 150 W.

Project 3.3 Ultrasonic characterisation, field measurements and quantification of dose

Services provided to industry, including rapid acoustic output determination for UK manufacturers of medical ultrasonic equipment, and specialist testing services, requiring the application of unique hydrophones, will continue to be provided and extended in key areas. The uncertainty of acoustic output measurements provided by a range of Measurement Services will be improved through the implementation of deconvolution techniques. Improved procedures of characterisation of physiotherapy treatment heads, specifically for small transducers exhibiting very divergent acoustic fields, will be developed and fed into the standardisation process. Services providing reference measurements of the ultrasonic properties of materials, and the assessment of heating caused by medical ultrasound equipment using tissue equivalent Thermal Test Objects, will be maintained. For compliance with recent International Standards, a service will be established for use by industry for the measurement of surface heating generated by diagnostic equipment and this will include a detailed evaluation of uncertainties. Reference standards for ultrasonic speed of propagation will be investigated and made available to industry. As a long-term look at the future requirements for ultrasound metrology in assessing the imaging performance of diagnostic ultrasound equipment, an assessment will be undertaken of the needs for calibration and characterisation services.

Project 3.4 High power ultrasound and acoustic cavitation

Leading-edge research investigating the development of new measurement and monitoring techniques for determining the degree of acoustic cavitation within industrial high power ultrasonic fields, will continue. A key component of this will be the further evaluation of NPL's novel patented cavitation sensor technology, to establish a better understanding of the stability, lifetime and performance of the devices. This will be undertaken through collaboration with universities and industry and further exploitation of the technology, for higher frequency applications potentially extending up to 1 MHz, will be investigated. Collaboration, both with industrial and academic partners, constitutes a key feature of this project, and will be used to carry out a feasibility study of standardised methods for assessing the cleaning performance of ultrasound cleaning vessels, with the long-term aim being to develop simple, easily applied methods, appropriate for implementation at the industrial level.

4.4 Theme 4: Acoustical Standards Research

Unlike other themes, this theme concentrates on research topics, many of which have common features and span the main technical themes. Topics include:
- Acoustic emission;
- Optical techniques for acoustical measurement and calibration in air and water;
- New research areas in medical ultrasound;
- New science and technology based on silicon MEMS technology and wireless communication;
- Machinery noise measurement, including sound quality;
- Environmental noise measurement.

Project 4.1 Acoustic emission

Aims
This project aims to address the need for national measurement standards for acoustic emission. Key components will be:

- development of a robust traceable source for in-situ calibration, to replace the pencil lead break
- sensor calibration and characterisation, including optical fibre-based devices
- modelling of acoustic emission systems
- dissemination of key outputs.

Background
Acoustic emission (AE) measurement is widely used in industry to monitor the condition of safety-critical and production-critical systems such as pressure vessels, engines and high-speed machinery. It can prevent the need for unnecessary and expensive early shut down of plant, as well as providing the means to minimise expensive, and often dangerous, failures. Recently, there has been more interest in the use of AE as an in-service condition monitor and as an on-line process-monitoring technique. Examples of its use cover a wide spectrum, from monitoring of large pressure vessels, storage tanks, and large structures such as bridges and aircraft structures, to studying tool wear and composition of liquids.

Rationale
Acoustic emission measurement is potentially a very important technology for the future, with the recent increase in computer processing capability providing the opportunity for more sophisticated methods of data analysis. One factor hindering the greater use of AE technology is the lack of traceability. This is particularly important for safety critical and highly regulated industries, such as aerospace and off-shore industries. In discussions, representatives of these industries in the UK cite this lack of traceability as a major obstacle in implementation and adoption of these valuable techniques. Indeed, a leading aircraft engine manufacturer has indicated it is unable to employ AE as an NDT certification technique due to this lack of traceability.

The project in this three-year programme builds on the work of the 2001–2004 Acoustical Metrology Programme, a previous INTErSECT project on acoustic emission, and on a small co-funded project between NPL, Lloyd's Register of Shipping and Airbus UK.

Under the 2001-2004 Acoustical Metrology Programme considerable progress has been made in starting to address key areas of concern to industry and to provide solutions that meet their current needs. One of the major issues is their requirement for a more robust traceable reference source for in-situ calibration of AE measurement systems, to replace the flawed pencil lead break and its associated problems of repeatability and traceability. Full characterisation of sensors in terms of in-plane and out-of-plane displacement sensitivities is also vital if informed decisions on transducer selection are to be made. This programme will build on the current work, collaborating with industry to ensure that the developed reference source is suitable for use in the field, and that calibration services meet their requirements. In the longer term optical sensors based on fibre technology may provide attractive alternatives to current day AE sensors, but it is essential that these devices are suitably characterised and calibrated. NPL will collaborate with industrial partners to research and develop suitable methodologies.

Knowledge of the type of excitation and how the sensor responds to such an excitation is key to understanding the signal produced by an AE sensor, and the current programme has investigated the potential for modelling small reference systems. These techniques will be extended to incorporate larger and more complex structures, and investigate the possibility of using molecular modelling techniques to model fracture type events in engineering structures. If successful this would provide an extremely useful and very powerful tool for industry.

Close links with industry, together with raising awareness, consistency and improved measurement practice among the user community are key to the development of acoustic emission as a recognised technique. These issues will be addressed by a number of knowledge transfer exercises, including an acoustic emission forum, input to standardisation committees and various web-based initiatives.

Project 4.2 New generation of acoustical measurement standards

The main aims of this project are to:

- develop optical techniques as the basis of new measurement standards for the calibration of airborne and water-borne measuring instruments
- establish proof of feasibility for photon correlation as a primary standard for airborne sound
- develop optical vibrometry as the basis of a new primary standard for underwater acoustical calibration above 1 kHz
- establish an increased understanding of the acousto-optic interaction for applications of cross-beam vibrometry to: 2D/3D beam profiling, non-linear focused fields and in the near field
- develop a clinically relevant bone phantom for assessing the performance of ultrasonic equipment used in osteoporotic screening.

Background

The reciprocity method has become the standard method for calibration of microphones or hydrophones.

For sound in air, the calibration method that has become recognised internationally is coupler reciprocity, where calibration is undertaken essentially in a closed coupler. This is a simple calibration technique that has been developed and refined over many years to realise the pascal to an accuracy unsurpassed by any free-field technique, and it is the basis of UK NMS primary standards, see Theme 1. Traceable calibrations of devices such as microphones, sound calibrators and sound level meters are mainly achieved by pressure-based techniques using a calibrated reference microphone. However, the calibration of non-standard microphones is not easily accommodated by these methods because of coupling considerations, and this is quite a restriction and an inhibitor to the introduction of new technology. Furthermore, calibration of miniature array microphones or MEMS sensors is also not possible. These limitations would be overcome if free-field calibration techniques could be implemented more easily, and this can be achieved using optical techniques as they offer the ability to realise an accurate determination of the pascal at a point in a sound field.

For sound in water at kilohertz frequencies, primary calibrations of hydrophones and transducers are currently based on free-field reciprocity techniques (see Theme 2). The headroom between the primary standard and the typical uncertainty provided in calibration services is relatively small. In order to meet the most demanding industrial and traceability requirements, the primary standard must be realised with improved uncertainties. As with sound in air, it would be preferable to realise the primary standard by basing it on the determination of a fundamental acoustic quantity at a point of interest in the sound field. Again, this can be achieved using optical techniques and pilot work undertaken as part of the NMS Quantum Metrology Programme (Project 3.6) has shown that optical vibrometry applied to a thin pellicle in water is the way forward.

Rationale
For sound in air, photon correlation methods have been developed to the point at which a prototype system can now be developed as a method of improving the accuracy of primary acoustical standards, and thereby enabling them to be more accurate and directly traceable to SI base units. Scattering of light from natural particles in the air as they pass through a fringe pattern established by two intersecting laser beams will be used. There will be a need to undertake research studies on particle size and concentration, signal-to-noise and photon correlation signal analysis techniques. Implementation and testing of a pilot facility in the small anechoic chamber at NPL will be the ultimate objective.

For sound in water, it is proposed to implement, test and validate a specially developed laser vibrometer based on optical fibre technology as the basis for a new primary standard for underwater acoustical calibration above 1 kHz.

A key issue for all optical methods is achieving an understanding of the relationship between the optical signal received and the sound field disturbance. This is especially important in situations where the acoustic field is highly complex, for example in focussed fields, non-linear fields or in the near-field of transducers, where the field is far from plane-wave. It is well established that the interpretation of the optical signal in a plane progressive wave and the optical beam is parallel to the acoustical propagation direction. In more complex fields, it is vital that the physics of the acousto-optic interaction is thoroughly understood in order for the measured data to be correctly interpreted, and considerable further work is required before a complete understanding is gained. This is important as the foundation for future wider application of optics for acoustic measurement. In the long term, optical techniques have the potential for 2D/3D acoustic field mapping in the Acoustic Pressure Vessel.

Finally, in medical ultrasonics, the need for a reference method of assessing of ultrasonic equipment used in osteoporotic screening will be undertaken through the development and characterisation of a clinically relevant bone phantom.

All projects are expected to be undertaken in collaboration with other groups.

Project 4.3 New generation of acoustical measuring instruments for sound in air

The main aims of this project are to:
- develop a new generation of acoustical measuring instruments for sound in air based on silicon MEMS technology and wireless communications
- achieve a matchbox-sized wireless device with on-board microphone and temperature sensor
- evaluate the performance of the new sensor against conventional acoustical instruments
- work towards the next stage of multi-variable sensors capable.

Background
For over 40 years, the condenser microphone has been the laboratory and working standard measuring device for airborne acoustics. Hence, microphones, sound calibrators and sound level meters have become the centrepieces of acoustical metrology. The limitations of these systems are that they are expensive, difficult to deploy in large numbers and physically quite large. The inability to deploy a larger number of measuring devices often leads to larger measurement uncertainties in many machinery noise, environmental noise and room acoustic measurement situations. Many of these modern acoustical measurement challenges could be overcome if small, cheap, remotely deployable and easy to use measuring instruments were available.

Rationale
The development of a new generation of acoustical measuring instruments based on silicon MEMS technology and combining these with wireless communication to a central console would overcome many

of the current limitations. Typical performance characteristics would be:

- Small (button-sized) silicon-based acoustic sensor (MEMS) integrated with on-chip signal processing capability;
- Performance properties suitable for acoustic measurement;
- Remote operation - wireless communication;
- Multi-channel capability;
- Additional sensing of particle velocity and other parameters such as temperature, atmospheric pressure etc.;
- Cheap, robust and easy to use.

Whilst this is a formidable list of characteristics, to make progress, not all of these need to be achieved in the first instance. It is proposed to undertake the development of MEMS-based sensors in two main stages:

First generation MEMS-based acoustical measuring instruments
Small silicon MEMS acoustic sensor with on-board temperature sensor (initially matchbox size);
On-board processing – amplification and filtering;
Wireless transmission to central control.

Second generation MEMS-based acoustical measuring instruments
Even smaller MEMS sensor systems (maybe 10-15 mm size);
Combined acoustic pressure, particle velocity, compensation for temperature and other environmental parameters;
Relative position monitoring between sensor groups.

There are many challenges during this type of development. Issues include the increased complexity of on-board processing, device operational management and power dissipation management, interference in operations electrically noisy environments and in the vicinity of large metallic structures.

The plan within this NMS Programme is to realise the *First generation* of MEMS sensors at 'matchbox size'. This will enable the performance of devices simulating a sound level meter to be assessed and an appreciation of operational issues gained. This will be achieved through collaborative projects involving academic and industrial groups with established capability in the important silicon MEMS and wireless technologies. The *Second generation* poses greater risk and requires further research and development especially for the silicon sensors capable of additional variable sensing etc. This will be achieved either in follow-up NMS Acoustics Programmes (subject to the success of the *First generation*) or if possible more rapidly through parallel programmes where funding from other sources (industrial and government) will be sought.

Examples of how these MEMS-based measuring instruments might be used are:

Noise emission: A large number of small 'button-sized' sensors could be deployed around a machine to provide greater spatial sampling. One might envisage space-frame panels of sensors being used to simplify deployment. *Second generation* sensors able to measure true intensity would allow sound power to be determined in complex environments.

Noise immission: Sensors could be deployed at a larger number of sites. Being small, the sensors would be less vulnerable to being stolen or interfered with. The *Second generation* devices could record more of the relevant environmental parameters.

Room acoustics: A three-dimensional space-frame of sensors could be used to average the acoustic field to overcome room resonances.

Audiometry: Whilst not an initial objective, specially-developed in-ear MEMS sensor systems could be developed to allow new audiometric measurements to be made.

Calibration: MEMS devices could be calibrated at the highest level using a sound source in a free field room and with the sound field calibrated absolutely using optical techniques (potential to be an automated process), see Project 4.2. Simpler free-field techniques could be used in an open space especially as small sensors will have broad frequency response and could be operated in tone-burst or pulsed mode, thereby eliminating the need for a free-field room.

Project 4.4 Improved methods for quantifying noise emission from machines and products

Aim

The aim of this project is to improve methods for quantifying noise emission from machines and products by delivering both short to medium term solutions as well as driving the development of new measurement technology and striving to eventually resolve many of the issues posing barriers to industry. The expected outcome will firstly benefit UK industry offering more efficient, accurate, and reliable measurement techniques enabling improved noise emission diagnosis and low noise design, but the benefits will then extend further. The UK workforce and community will in future benefit from reduced machine and product noise emission levels, leading to improved health and safety conditions and quality of life.

Background

There is an increasing global awareness that the effects of noise can be hazardous to health and impact significantly on quality of life. In the UK, an extensive body of regulations, many of which implement the requirements of EC Directives, are in place to control noise, imposing limits on the noise emission levels from specific sources such as vehicles, industrial machinery, and domestic products. Most commonly noise emission measurement is required to protect the health and safety of the workforce and public, but it is also necessary to enable improvements in product design, and to provide data for noise immission prediction and assessment.

The Physical Agents (Noise) Directive, due to be implemented as UK regulation in 2006, to replace the Noise at Work Regulations 1989 with more stringency, sets out the requirements for employers to manage risks arising from noise, stipulating the need for noise assessment. A number of EC Directives (e.g. 89/392/EEC, 2000/14/EC) require manufacturers to make measurements in accordance with international specification standards such as the ISO 3740 and ISO 9614 series so as to provide information on sound power level of their products as evidence of compliance with health and safety requirements. Furthermore, it is a requirement that noise labels are affixed to many machines and products showing the guaranteed sound power level and that a declarations of conformity are issued. Measurements to obtain this information are a prerequisite for placing the machine on the market. Where the noise levels generated by a machine are unacceptable, non-standard diagnostic measurements will often be required to determine comprehensively, the noise emission characteristics of the machine, to enable effective implementation of noise reduction techniques and to improve product design. Low noise level and ‘sound quality’ are known to be an important issue for consumers and effect the overall decision of purchasing a product.

Rationale

The process of consulting with many sectors from UK industry confirmed that measurement of noise at source continues to pose problems in practice. The complexities associated with measuring noise emission from machines and products in real situations can lead to uncertainty and concern over accuracy. The increasing pressure placed on industry to make noise emission measurements to meet the requirements of EC Directives and UK Regulations is causing industry to question current measurement methods and technology available.

Compliance testing in accordance with regulations using measurement methods set out in current specification standards, and the recognised importance of low noise and sound quality design in product development, add to production and operational costs, placing an economic burden on UK industry. Efficient and accurate methods of measurement are essential for UK industry to operate competitively. Existing methods such as sound pressure and sound intensity can lead to large uncertainties for certain situations, particularly large sources. There are practical difficulties where for example extraneous noise can be a problem with the measurement result contaminated by unwanted contributions from other component noise sources. Particular concerns about accuracy and the amount of measurement effort required, using current techniques, need to be addressed, both in the short and long term.

The research proposed supports this principle of developing new technologies and solutions for the reduction of noise emission, delivering both short term solutions to the practical measurement issues as well as the drive for development of new measurement technology, which will eventually resolve many of the difficulties posing barriers to industry.

There is an ongoing desire for simplification of noise emission standards, and a long-term vision that selection of a measurement set-up should be less restrictive. Initial steps are currently being made to evaluate uncertainties associated with various methods. With further endeavour the principle of floating uncertainty could be realised where the user of the standard would have information on the level of uncertainty and accuracy for a given measurement configuration. Information needs to be fed directly into the improvement of the existing international specification standards benefiting industry obliged to use the methods.

It is important that industry have available, accurate and efficient source characterisation technology to encourage innovative solutions to further reduce the noise output of machines and products in line with EC noise policy. Research proposed will examine the validity of using existing airborne noise emission measurement methods for characterising a range of industrial sources. Practical measurement problems and the current state of knowledge with regards dominant sources of uncertainty will need be considered. The output of the work will identify priority research and development support needs.

Research will be conducted to investigate new and more adequate measurement techniques to improve upon current methods for characterising complex industrial noise sources. Consideration will be given to the unified approach of quantifying airborne, structure-borne, and fluid-borne noise to characterise emission processes inherent with real machines. The feasibility of using alternative measurement techniques (e.g. Microflown particle velocity sensors, and laser vibrometry) and technologies will be investigated.

Acknowledging the growing employment of sound quality techniques in product design, an element of this research will be to expand on the work done so far under the current NMS on sound quality metrics, paying attention to validity of currently available objective sound quality measuring equipment, as well as demonstrating the benefits of employing psychoacoustic techniques in industrial product design.

Project 4.5 Improved methods for quantifying airborne noise immission

Aim

The aim of this project is to ensure methods used for quantifying noise levels in the environment are reproducible and robust, recognising the importance of the decisions made at Government level on the basis of the measured and predicted results. A significant effort will be to establish the potential for the application of new techniques and technologies to improve noise immission measurements, to benefit both the UK community and economy.

Background

Awareness of the effects of noise immission has increased in recent years, especially since “The Green Paper on Future Noise Policy” (1996), which identified that about 80 million people are exposed to noise levels considered unacceptable because they lead to sleep disturbance and other adverse health effects and that the annual economic cost of noise to society is more than 12 billion Euro. According to the

Chartered Institute of Environmental Health, local authorities in England and Wales reported receiving FIVE times as many complaints about noise in 2001/2002 than in 1982/1983.

The Green Paper proposed a framework for action to substantially reduce environmental noise, based on the principle of shared responsibility at national, regional and local levels, involving target setting, monitoring of progress and measures to improve the accuracy and standardisation of data to help improve the coherency of different actions. The most significant realization to date has been the approval of the Directive on the Assessment and Management of Environmental Noise (2002/49/EC). This has resulted in considerable activity throughout Europe, primarily focussed on the production of strategic noise maps for all major agglomerations. The maps will in future years be linked with other models including transport, air pollution, and health models and used for strategic decision-making enabling Government to take greater account of noise.

Rationale

Consultation with UK professionals involved in environmental noise has identified a variety of concerns about current methods and technology available to facilitate the measurement and prediction of noise immission.

An aspect of noise immission, which undoubtedly requires attention, is the measurement of low frequency noise in buildings, where views were received that current measurement techniques are unreliable, with poor repeatability and reproducibility. Such concerns are noteworthy, considering the recent changes to the Building Regulations, which introduced the need to measure and assess noise at lower frequencies. Whilst no specific work is planned on this topic, the development of the MEMS-based acoustical measuring instruments, see 4.3, will provide new methods of measurement by allowing a large number of measurements to be made over the volume of the room, say by the use of sensors placed on space frames.

Having historically received less attention than transportation sources, there is a need to assess the quality and validity of industrial noise prediction methods currently used in practice to assess how a new development or installation will impact on the local surrounding environment. Consideration is needed with regards uncertainty of the prediction methods, the reliability of algorithmic implementation in software, and the representation of frequency content, complex emission characteristics and acoustic features. The work will help to establish the potential for improvements in the techniques to predict accurately and reliably.

4.5 Theme 5: Knowledge Transfer

Aims and Rationale

Knowledge transfer provides the vital route for dissemination and exploitation of NMS results. It ensures that key beneficiaries are identified and kept informed of recent advances, raises general awareness of the NMS, and allows outputs to be effectively disseminated to companies and other organisations in the UK for the benefit of industry and wider society. Within the Acoustical Metrology Programme this will be addressed in two ways – dissemination of project specific outputs within the technical themes and dissemination of more generic information within the Knowledge Transfer Theme. Within the technical themes several knowledge transfer tasks will be managed as an integral part of projects, concentrating on take-up of specific projects. However, the need for generic knowledge transfer tasks cuts across the programme, both in terms of dissemination and information gathering, and these projects will be included within this theme. In all cases, it will be vital to identify the objective for disseminating the output, the target audience, the best route(s) of transfer appropriate to that audience, and to ensure material will be presented in the most suitable way.

The purpose of Theme 5 is therefore to apply knowledge developed and maintained within the programme to assist business, users and industry to:

- improve products and services in terms of technical performance and to ensure they are fit-for-purpose
- help reduce development, production and service costs/timescales
- improve the efficiency of meeting regulations
- support safe and effective diagnostic/therapeutic medical procedures
- support valid environmental and safety-related measurements
- provide for worldwide acceptability of products and services.

The work carried out under the technical themes will provide traceable measurement standards for a wide range of industrial, health-related, environmental and safety applications and these are continually developing in response to new requirements. The outputs of these technical themes take many forms, such as services, publications, new sensors/instruments, new methods, materials and data. Five main objectives have therefore been identified for the Knowledge Transfer Theme:

- Widespread adoption of good calibration/measurement/sensor design practice, nationally and internationally;
- Exploitation of programme R&D - new methods, new sensors/instruments, new materials, new data;
- Take-up by customers of services developed under the programme (calibration, measurement, sensor design/modelling);
- Ensure consistency of measurement and testing standards nationally and internationally and promotion of their use;
- Broader dissemination and information gathering.

Four key routes will be used for transfer of technical knowledge/capability to encourage the use of best measurement practice in acoustics and to ensure the benefits of the programme reach as many end-users as possible:

- The worldwide web – through the NPL Acoustics website (www.npl.co.uk/acoustics);
- Publications - scientific papers, reports, newsletters, magazine articles, guides, standards, technical information sheets, press releases (paper and/or web distribution);
- Events (collective customer contact) - courses, seminars, conferences, exhibitions, measurement club meetings, open days, practical workshops, industrial visits, thematic group meetings, press launches;
- Individual customer contact - telephone, email, mail shots, customer visits, demonstrations, one-to-one tuition, staff exchanges and secondments, R&D collaboration, loan of equipment (into and out of

the projects), sale of products (instruments, sensors, materials), sale of services and technical enquiries.

Project 5.1 Use of harmonised measurement and testing standards

Representation on international committees and standardisation bodies (BSI, ISO, IEC, CEN, OIML, WFUMB, ICRU, EUROMET) forms a fundamental and vital part of knowledge transfer. New standards can have significant direct impact on new products, or indirect impact through being called up in regulations or EU Directives. UK interests must therefore be represented and supported. Work will also continue within the Consultative Committee on Acoustics and Vibration (CCAUV) under the International Committee of Weights and Measures (CIPM), which plans and co-ordinates international key intercomparisons in acoustics and vibration. The results of these intercomparisons are published on the International Bureau of Weights and Measures (BIPM) website, to underpin the international Mutual Recognition Agreements. This database enables anyone to access information on the degree of accord between primary standards held by national measurement institutes world-wide. The UK Acoustics Contact Person to the European regional metrology organisation, EUROMET is provided by NPL.

Project 5.2 Broader dissemination and information gathering

The 2001 - 2004 Acoustical Metrology Programme has seen a vast increase in the use of the worldwide web, with a corresponding fourfold increase in web hits. The web is now one of the primary mechanisms for communication, and it is vital to knowledge transfer that efficient and effective use is made of this medium. It serves not only as a means of updating current customers and contacts on progress and introducing new customers to the NMS, NPL and Acoustics, but can also provide basic acoustical training, best practice in various techniques and practical measurements, as well as interactive guidance. Current site material will be continuously updated and extended, and it is planned that an FAQ facility will be introduced. For training purposes various ‘How to …’ guides will be added - often as a result of specific projects within the main technical themes and often in collaboration with industrial partners. All acoustics publications, papers and NPL reports are listed on the web pages, with abstracts shown where available, and wherever possible conference presentations will also be included. In some cases, reports and articles are available on-line, and there is an on-line form for requesting NPL reports free of charge. An on-line calculation of the speed of sound in sea water and pure water is also available in the technical guides area, and these interactive guides will be extended where applicable. The web pages also include up-to-date information on all measurement service and sales capabilities, and points of contact.

Publications are another vital dissemination route and the successful acoustics newsletter - which reaches over 4500 contacts - will continue. It is also important that dissemination of items within the current programme continues, and a CD will be produced of highlights from the 2001 - 2004 Acoustical Metrology Programme as well as an introduction to the 2004 - 2007 programme.

Cascading information via intermediaries such as professional bodies, trade associations and instrument manufacturers has long been recognised as a very effective means of reaching a large, relevant audience in terms of their membership or customers. The intention therefore is to maintain the important links between the programme and the Institute of Acoustics, British Society of Audiology, Institute of Physics and Engineering in Medicine, and British Medical Ultrasound Society, including providing technical contributions to their publications when applicable. The NMS Programme, through NPL, has close links with the IoA Measurement and Instrumentation Group and the Underwater Acoustics Group, whose activities have included the organisation of a number of very successful technical meetings, and the aim is to collaborate in the organisation of events where relevant. Active involvement in these Groups will continue as a means of reaching an even wider audience.

The three existing Acoustics Measurement Clubs provide opportunities for direct interaction with both existing and future customers in sound-in-air, ultrasonics and medical ultrasound, and underwater acoustics, and each Club will meet once during the programme. These popular long-standing one-day meetings are free to participants. They provide an opportunity to discuss current and future NMS-related work, provide tours of facilities, and give the chance both for dialogue with groups and individuals, and to gain important feedback from these key groups.

Provision of training courses in key areas also provides a very valuable service to the user and measurement community. Also, programme staff receive a large number of technical enquiries about measurement methods, measurement problems, suitability of measurement equipment, specification standards and many varied industries and customers benefit from advice obtained from the acoustics technical enquiry service, which will be maintained.

On a broader front, many industrial and business sectors can benefit from outputs from several NMS Programmes across NPL. It is therefore important to support cross-programme KT activities to promote and raise awareness of the various relevant activities.

Project 5.3 Impact assessment survey

It is also important to obtain some formal assessment of the effectiveness of the Acoustical Metrology programme KT, both in terms of its economic impact on UK industry and of increasing awareness of the NMS. An independent survey will be commissioned in the final year of the programme to research these issues.

4.6 Theme 6: Programme Management and Development

Aims
The aims of this theme are:

- to manage the delivery of the whole programme and to ensure that objectives are met within time and budget
- to ensure best value for money and to provide regular project and milestone progress and financial reports to NMSD
- to assist the DTI in the identification and procurement of the most effective programme of work for the available budget consistent with the agreed objectives of the NMS Acoustical Metrology Programme
- to organise the work into a logically structured and documented programme consistent with the agreed objectives and to assist DTI in prioritising that work
- to undertake a study related to improved dissemination of NMS standards to UK plc.

Project 6.1 Programme Management

This project provides the overall coordination functions for the NMS Acoustical Metrology Programme, monthly and annual reporting on progress, and general liaison with NMSD. This will include promotion of the objectives of the programme, monitoring the progress of all contractors on behalf of NMSD, liaison with NMSD on all technical and financial matters, and proposals to NMSD for programme modifications resulting from changing circumstances.

Project managers are expected to incorporate the necessary financial, operational, and quality management tasks within their projects and to report to the overall Programme Manager at three monthly intervals or as necessary to facilitate provision of the above reports.

Within the core programme carried out at NPL, the Programme Manager will plan, manage and coordinate the manpower resources, non-staff resources and capital requirements required to ensure that the programme is delivered on schedule, liasing with NMSD as necessary.

A study will be undertaken to explore ways of improving the dissemination of NMS acoustical standards to UK plc. This will look at both national and international devolution.

Project 6.2 Programme Development

This project deals with the formulation of the next Acoustical Metrology Programme (2007-2010) and will be formulated 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. The specific details of the process will be established in consultation with the NMSD, and is likely to involve thematic group meetings held in September 2007.

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.

Project 6.3 KT theme management and reporting, and interaction with NMS KT

This Project covers the management of the cross theme KT disseminated within theme 5, including the necessary financial, operational, and quality management tasks associated with the projects. It also covers reporting to the overall Programme Manager as necessary, and the provision of expanded reporting on KT within the Annual Report. In addition, it ensures that the programme interacts effectively with the overall

NMS KT programme, looking for synergies of audience, sharing best practice and contributing to appropriate joint activities.

ANNEX A: Other projects and areas of mutual interest between the NMS Acoustics and other NMS Programmes

A1. Other projects

Two specific project ideas are outlined below which have arisen during the later stages of formulation of the NMS Acoustics Programme. Both are topics that are ideal for consideration for inclusion when the opportunity arises during the three-year programme, and they could be expected to be undertaken in collaboration with industry and academic groups.

Acoustic emission for damage assessment and material property measurement

This would involve the development of accurate methods for pattern recognition and simulation of AE events under static and fatigue loading conditions in metals and fibre-reinforced plastic materials. This work would involve controlled experiments in which defects of known type, size and location would be introduced into specimens and tested under known loading conditions in order to identify the AE signature associated with the defect. Miniaturised artificial AE sources for simulating these signals would then be developed in order to enable traceable calibration of these AE sources.

Drivers

- Safe operation of plant
- Remote monitoring of damage
- Cost effective inspection procedures

Technical Issues

- Acoustic emission signal interpretation
- Transducer performance
- Reference systems and standards

Possible Outputs

- Guidelines for intelligent use of AE monitors

This project would be undertaken in collaboration with materials experts in the NPL Division of Engineering and Process Control. Four potential industrial collaborators and one academic partner have been identified.

Simplified methods of characterising NDE ultrasonic transducers

Currently, there are no recognised standard methods of characterising the performance of NDE ultrasonic transducers in a traceable manner. Although full acoustic characterisation of the transmitted ultrasonic field is possible, this is totally impractical as an industrial method. With the continuing growing need for traceability in NDE testing, simplified methods are needed which provide valuable reference information for the user and manufacturer of transducers. Prof Larissa Fradkin at South Bank University has been developing methods of predicting key features in the transmitted ultrasonic field using simplified methods, effectively like ray tracing. There are now ideas about how to tackle the inverse problem of taking measured key features in the transmitted field and predicting the transducer properties that would give rise to such features. By making a few selected measurements in the spatial and time domains, it may be possible to characterise transducers and effectively provide traceable performance indices. Ultimately, this could provide a whole new method of providing traceable calibrations for NDE transducers, and maybe medical ultrasonic and underwater acoustic transducers. This would provide a natural extension of the work undertaken in the NMS Acoustics Programme in ultrasonics and acoustic emission, but aimed initially at NDE transducers, for both compressional and shear wave types.

The project would involve development of the inverse prediction methods at South bank University and the validation of the methods using facilities developed under the NMS Acoustics Programme. The project would be undertaken in collaboration with industry partners.

A2. Topics of mutual interest between the NMS Acoustics and other NMS programmes

As in many areas of metrology, there are common interests between technical areas. As the metrology becomes increasingly multi-disciplinary, often an essential feature in order to exploit innovations in one area to the benefit of another, it is important to be able to review areas of common interest and develop methods of responding to changing requirements as and when the need arises. To this end, contacts with other NMS Programme Managers and individuals have led to the compilation of a table of areas of mutual interest, as given Table A1. The intention is that these topics will be reviewed during the three-year programme and opportunities taken to develop joint projects where and when appropriate.

The list of topics in Table A1 is not exclusive, and additional topics are expected to be added and will form the basis of a dynamic process of review and exchange of information as the programmes develop.

Table A1: Topics of mutual interest between the NMS Acoustics and other NMS Programmes

Programme	Topic
Materials - Performance and Characterisation	Use of acoustic emission to monitor cracking of oxides and protective coatings – interpretation of signals. Potential interests in Project 4.1.
Materials - Performance and Characterisation	Acoustic emission for damage assessment and material property measurement – pattern recognition and simulation of AE events under static and fatigue loading
Materials Processing - Metals; polymers and slurries	Using ultrasound for determining the cleanness of melts and also the measurement of viscosity.
Materials - Characterisation	Use of EMATs for metal texture measurement (EPSRC project with Warwick Uni. and Birmingham Uni.)
Flow- Ultrasonic flow meters	Ultrasonic flow meters
Flow - Cavitation	Cavitation
Mass - Barometric pressure	Dynamic pressure, comparison with low frequency acoustic standards
Mass - High pressure and force	Determination of elastic properties of hard materials using ultrasound – ultrasonic properties of materials
Mass - Hardness	Instrumented indentation hardness test for measurement of modulus - can be compared with an ultrasonically-derived values. Possible future work on room temperature creep and hysterisis of elastic materials, as it would provide an independent elastic modulus value.
Mass - Density	Speed of sound measurements as a means of relative density determination.
Length - traceability	Basic traceability for dimensions, volume, force.
KT	Sharing best practice on KT - KT Forum. Links in terms of common mailings, details of Clubs, training courses and activities.
Length (and Mass) – Laser vibrometry	Laser vibrometry developed under QM Programme to be used in acoustics and possibly applied to the NPL microfabricated balance as a transfer standard for nanoforce.
Biotechnology – Acoustic spectroscopy	The use of acoustic spectroscopy for biological product quality control.

Table A1 cont'd

Programme	Topic
SSfM – Continuous modelling	Continuous modelling – FE and boundary elements. Potential interests in Sub-projects 2.2.2, 2.3.2, 3.1.6, 3.2.3, 4.1.3 and 4.2.5.
SSfM – Data fusion	Potential interests in Project 4.1 (AE) and Sub-project 4.5.1 (Environmental noise)
SSfM – Good Practice in visualisation	Potential interest in Virtual Acoustic Modelling techniques, Sub-project 4.4.4
SSfM – Industrial uncertainty methodology	Potential interest in Sub-Projects 1.3.4, 1.3.6 and 1.4.8.
SSfM – Key comparison support	Sub-projects involved in Key Comparisons.
SSfM – Metrology software	Potential interest in staff involved in Sub-project 1.1.2 attending training courses.
SSfM – Data curation	Potential interest in integrity of data associated with pistonphone and sound calibrator calibrations, Sub-project 1.3.1.
SSfM – Signal processing	Potential interest in many projects involving DSP, Sub-projects 1.3.4, 1.3.6, 1.4.8, 3.3.5, 3.4.1 and 4.2.2.
SSfM – Internet enabled calibration	Potential future interest in new MEMS sensors, Project 4.3.
Thermal - Temperature in phantoms	Temperature rises in phantom tissues – thermal imagers and characterisation of phantom tissues – Sub-project 3.2.4
Thermal - Surface temperature	Surface temperature measurement, project 3.3.9
Thermal - multi-variable sensing	Novel multi-variable optical sensors, Sub-project 4.1.4.
Thermal - Internal temperature	Remote and internal sensing of temperature, deposition of energy by ultrasound
Thermal - Thermal properties	Thermal properties of materials used for phantoms.
Ionising Radiation - Environmental	Use of Wraysbury reservoir as a site of low background radiation for environmental monitoring R&D and Testing.
Ionising Radiation - DATA fusion	Potential future linking of imaging modalities – CT, MRI and Ultrasound.
All	Noise and vibration in laboratories

ANNEX B: Summary of Themes, Sub-Projects/Deliverables, Rationales and Activity Type

Key to annex B

This annex provides details of the proposed themes, projects and sub-projects. The activity type is also listed, these are:

P	Provision of standards
R	Research
R+	Research with long-term horizon (5-10+ years)
D	Development
I	International
KT	Knowledge Transfer
M	Programme Management