# The Acoustical Metrology Programme at NPL

## 1. The National Measurement System

The National Measurement System (NMS) is the United Kingdom'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.

## 2. Introduction to the Acoustical Metrology Programme

The Acoustical Metrology Programme is one of the three-year programmes of work for which the NMS acts on behalf of the UK Department of Trade and Industry (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 short report details the 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 and Themes.

### 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.

### 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

- 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

- 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

- 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 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 five technical Themes:

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

## 2.4 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.

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.

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.

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.

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. 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 2.4, a fifth covering cross-theme knowledge transfer.

The five technical 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.

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.

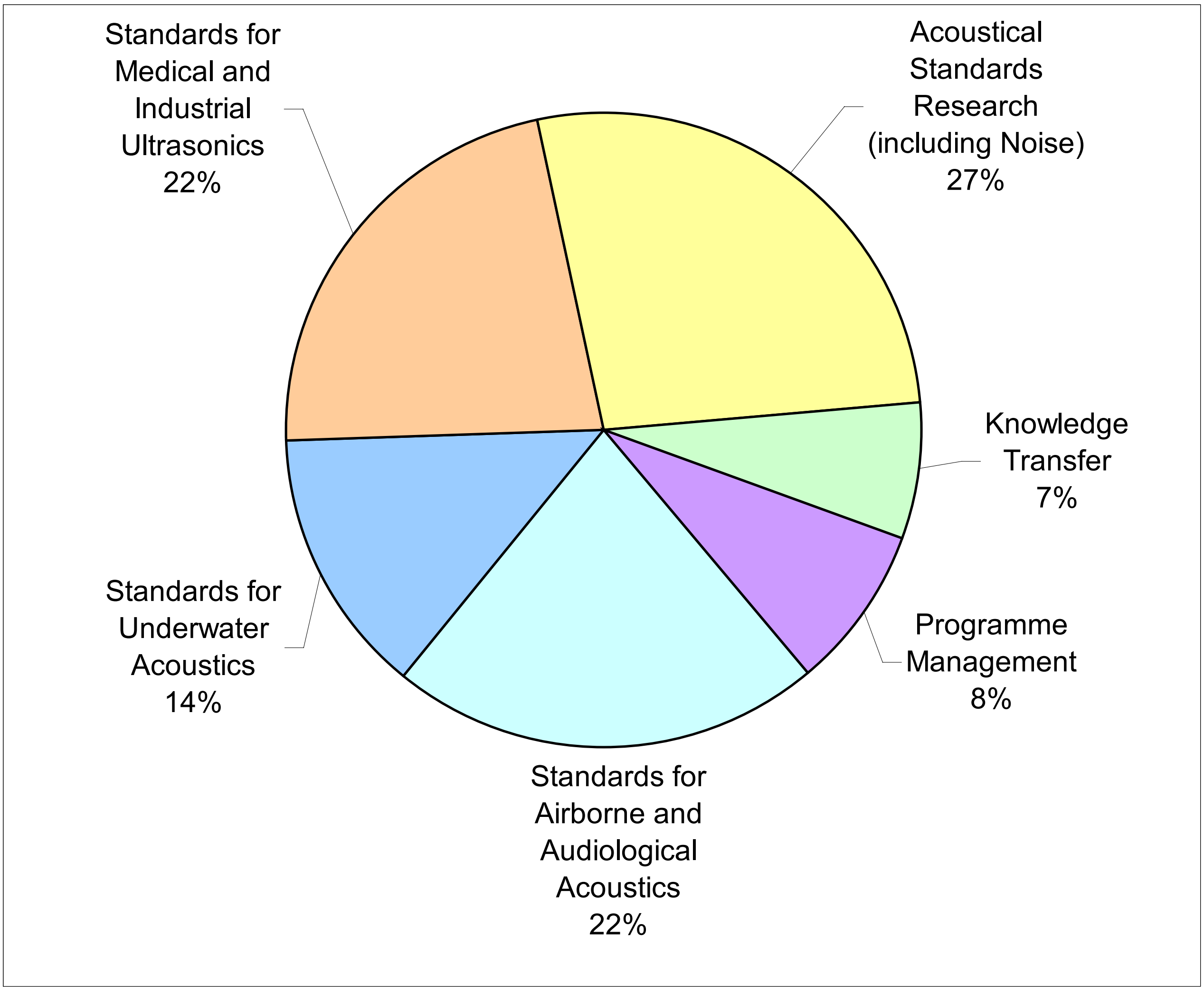


**Figure 1: Balance of the proposed programme by Theme**

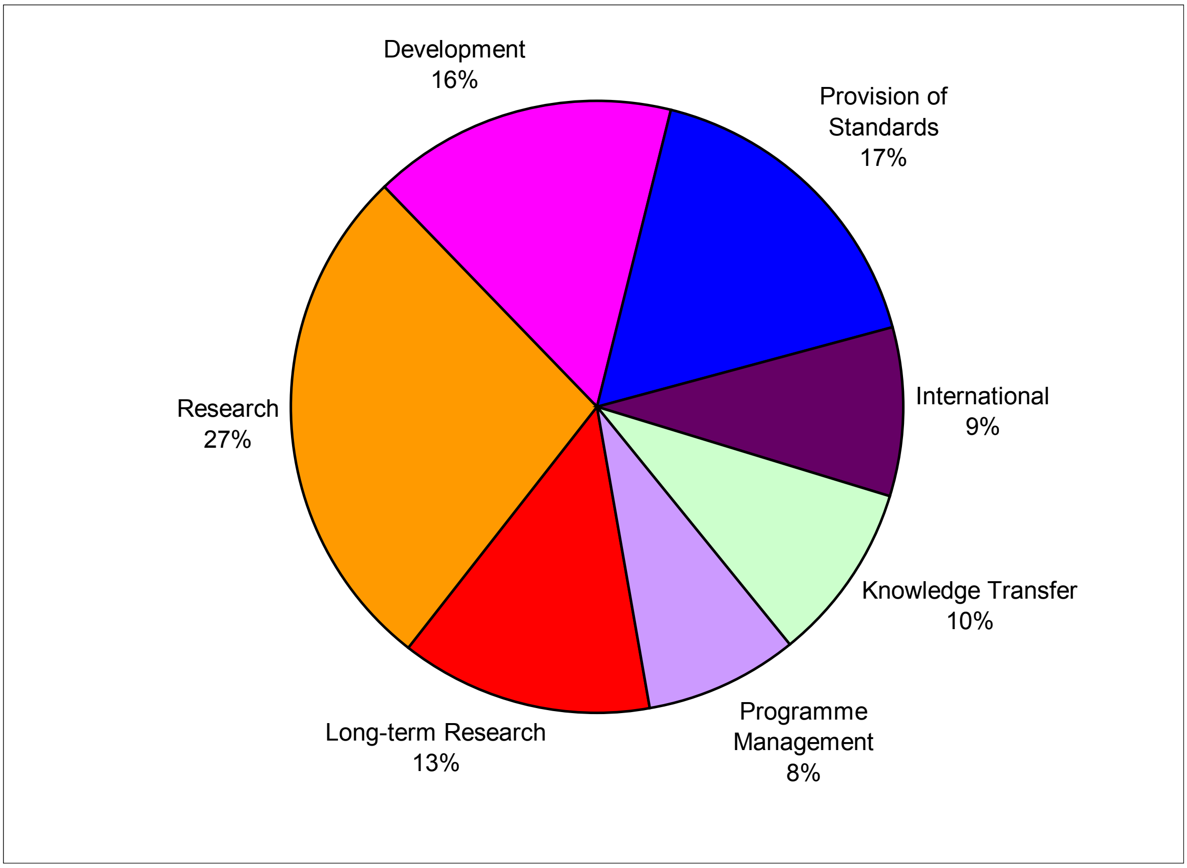


**Figure 2: Balance of the proposed programme by Activity**

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.

## 3.1 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.

**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.

## 3.2 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.

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.

**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.

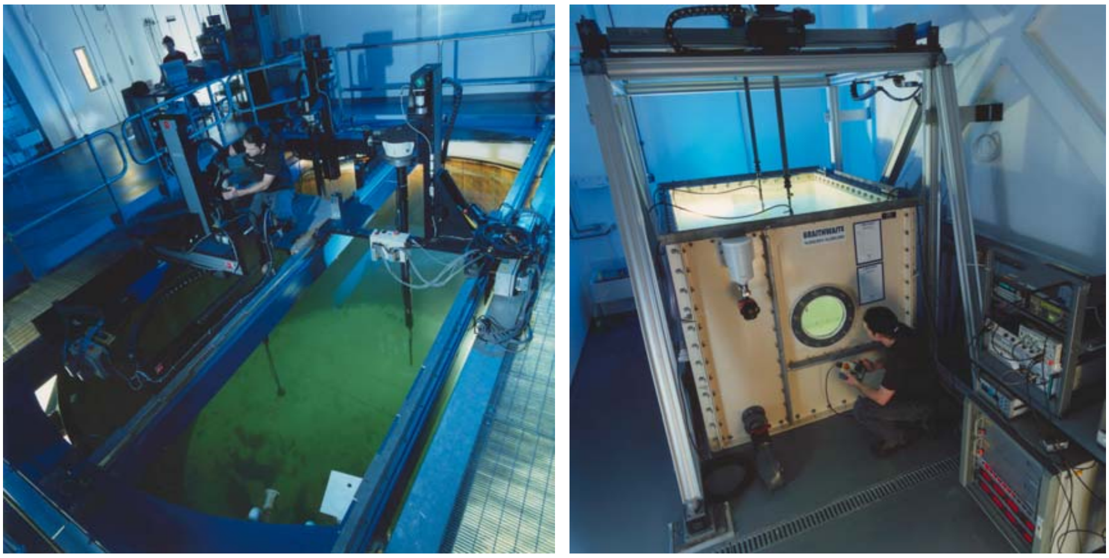

**Figure 3: Photographs of the new Open Tank Facilities at NPL showing the large tank (left) and small tank (right) and their respective positioning systems.**

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).

**Figure 4: The NPL open-water acoustic calibration facility located at Wraysbury reservoir.**

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.

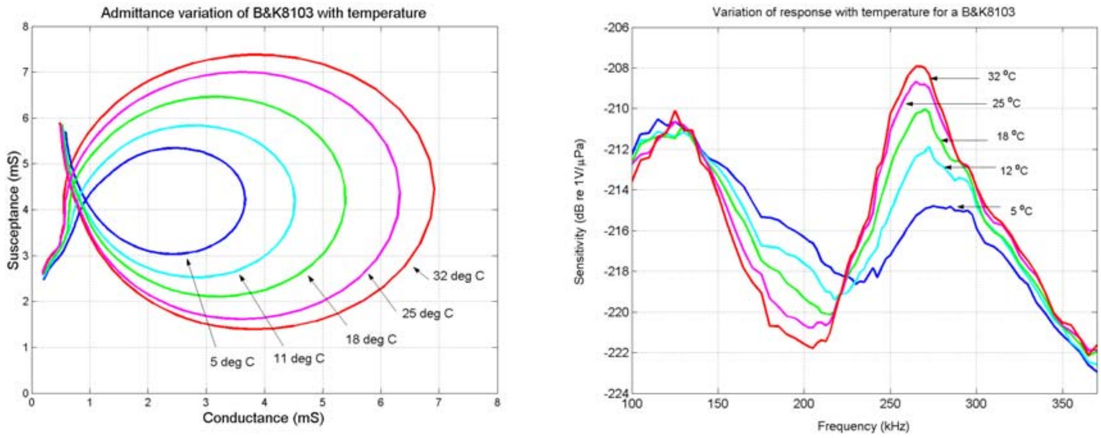


**Figure 5: Variation of electrical admittance and receive sensitivity with temperature for a B&K8103 hydrophone in the frequency range 100 kHz to 400 kHz measured using the NPL APV.**

## 3.3 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 the development of international specification standards;
- 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.

**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 to industry and hospitals 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.

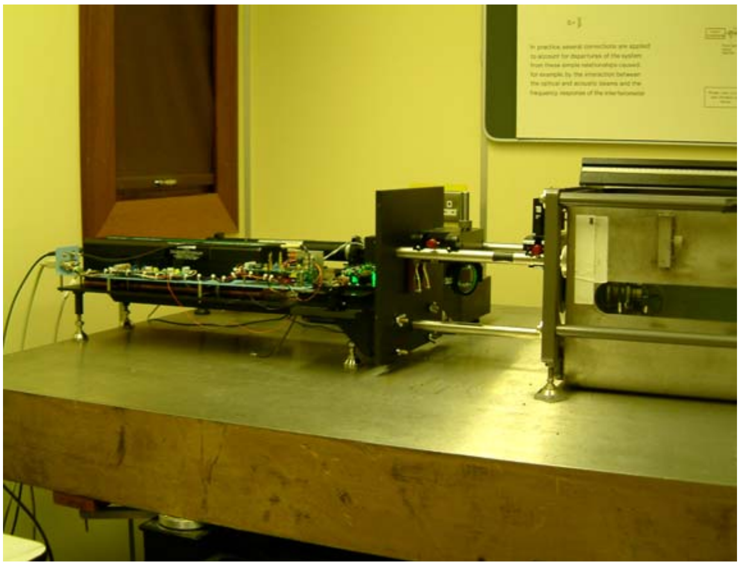

**Figure 6: Frequency doubled Neodymium YAG laser forming part of the new NPL primary standard laser interferometer for the calibration of ultrasonic hydrophones. The improved signal-to-noise of the new interferometer now allows calibrations beyond 40 MHz.**

**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.

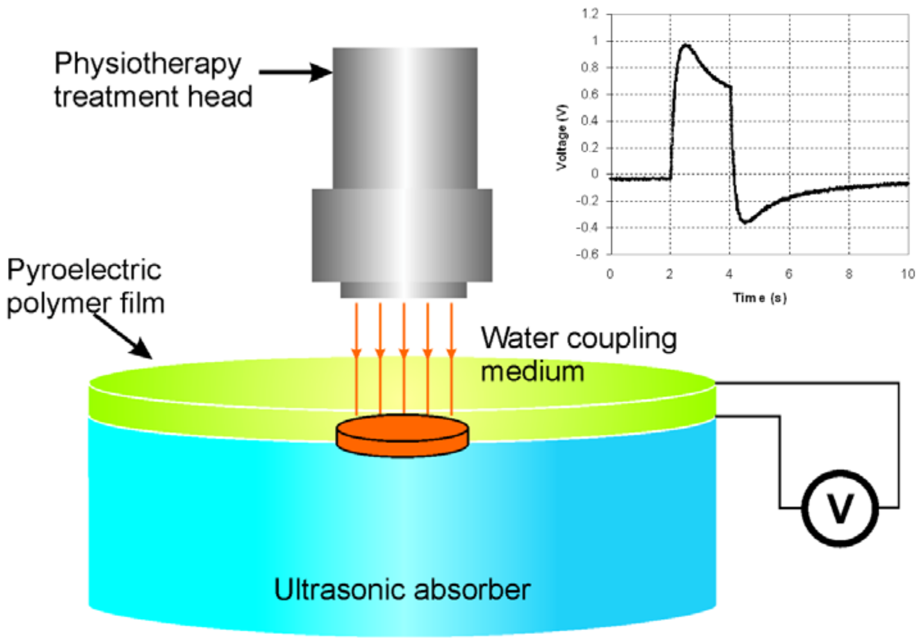


**Figure 7: Schematic for a novel, solid state based concept for a power meter suitable for application at the users level. The concept utilises the pyro-electric effect of *pvdf*, and the voltage generated (see insert, where power to the transducer is switched on after 2 seconds) by the film as it responds to a rapid rise in temperature produced by absorption of the ultrasound within an ultrasonic absorber adjacent to the *pvdf*.**

**Project 3.3 Ultrasonic characterisation, field measurements and quantification of dose**

Services provided to industry, including rapid acoustic output determination for 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. 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. 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.

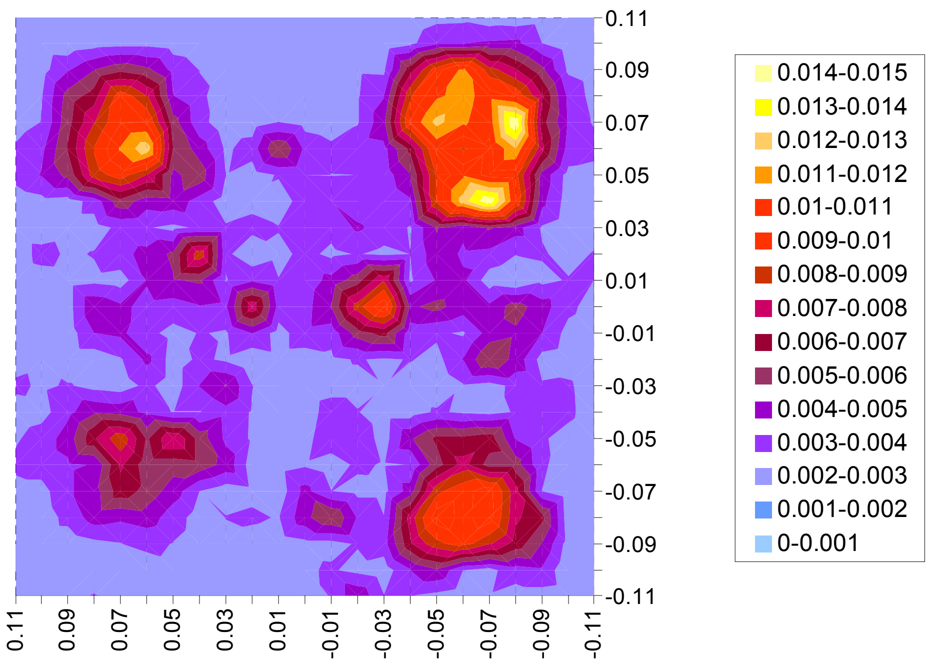


**Figure 8: Spatial mapping of the cavitation activity within an ultrasonic cleaning vesse oeperating at 40 kHz and an electrical power of 160 W, revealing the cavitation maxima over the four transducers. The measurements have been carried out using the NPL cavitation sensor, and is part of a programme aimed at developing methods of monitoring and controlling the application of cavitation within industrial and medical processes. Dimensions are given in metres.**

## 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.

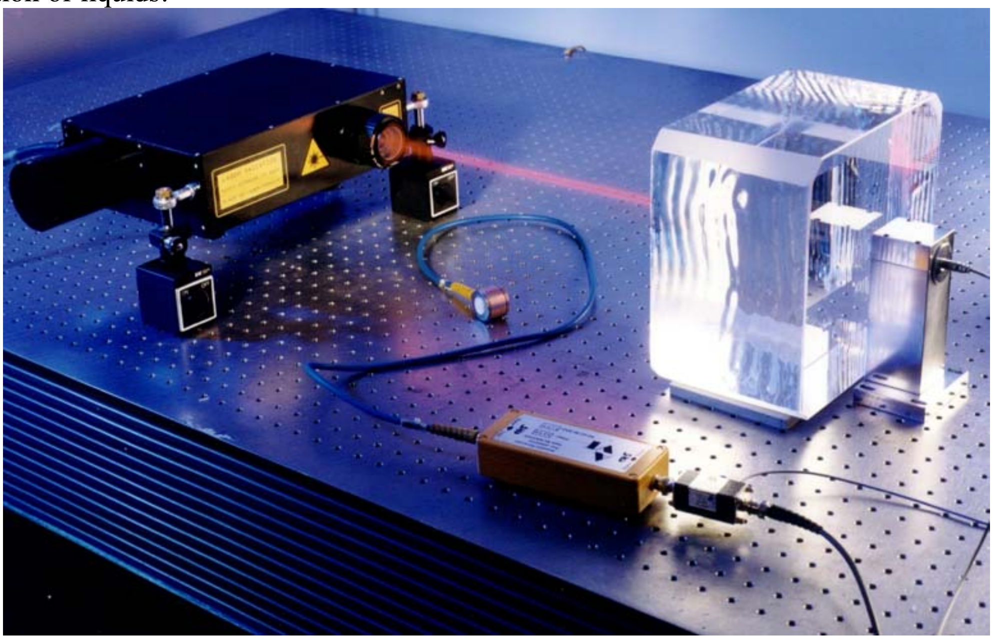

**Figure 9: Picometer displacement interferometer and glass propagation block used for research into calibration methods for AE sensors.**

**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 has shown that optical vibrometry applied to a thin pellicle in water is the way forward.

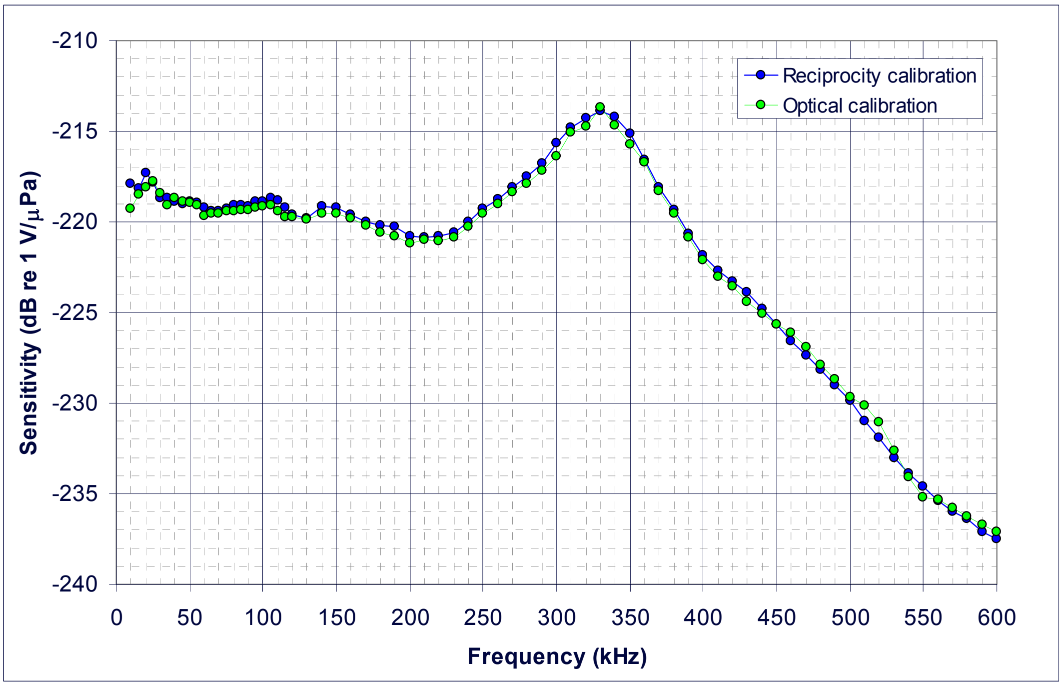


**Figure 10: Comparison of the results of calibrating a hydrophone by three-transducer spherical-wave reciprocity and by an optical method using laser vibrometry to measure the acoustic particle velocity.**

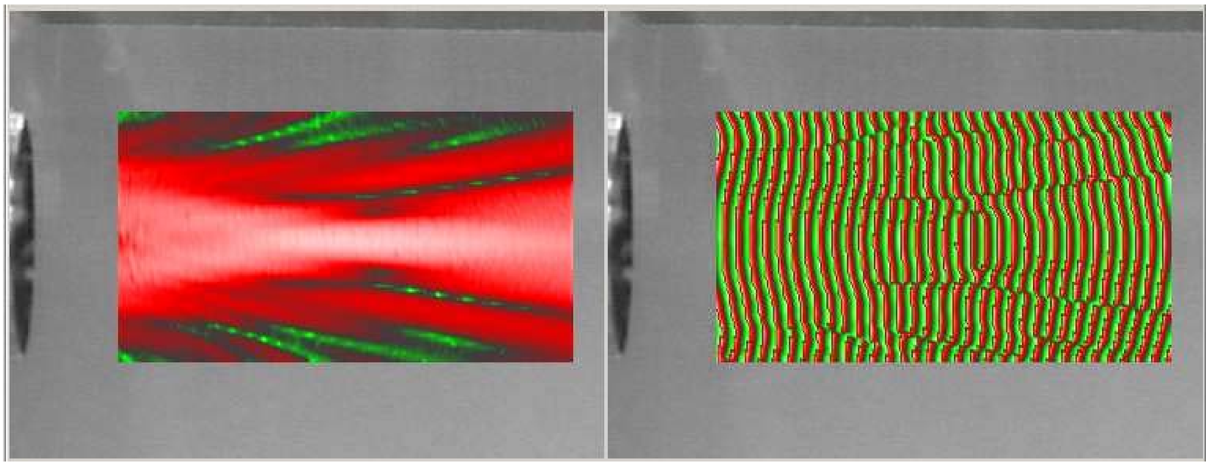

**Figure 11: Image of the acoustic field from a 600 kHz focused transducer showing the amplitude (left) and wrapped phase (right) of the field. The image was produced using a scanning laser vibrometer with the optical beam orthogonal to the acoustic axis of the transducer. The vibrometer is detecting refractive index changes integrated along the path of the optical beam.**

**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.

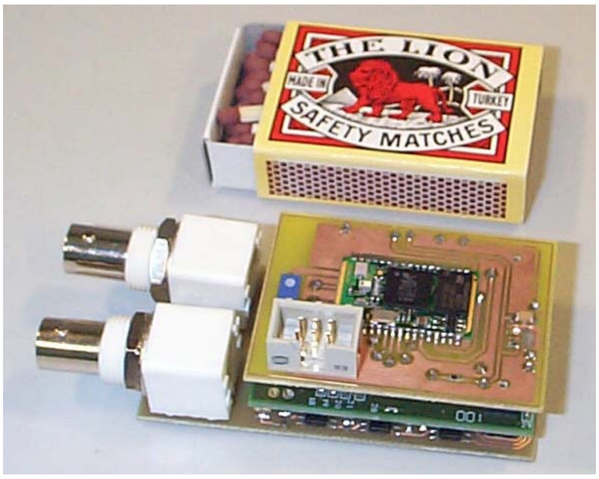


**Figure 12: Depiction of potential size of a first generation MEMS based sensor. The image illustrates the type of device which has been produced for other applications and is a wireless ultrasonic transducer (pulser/receiver). Photograph provided courtesy of Strathclyde University.**

**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(see Figure 3)*
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.

### 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.

## 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.