FUTURE NEEDS FOR METROLOGY IN ACOUSTICS, ULTRASOUND AND VIBRATION

1 Background

The CIPM document on National and International Needs in Metrology published in 1998 [1] was a first response to a mandate given by Resolution 11 of the 20th CGPM in 1995. That report focused the role of the BIPM and the need to improve the international harmonization in measurements, stating the basis for the Mutual Recognition Arrangement signed in 1999 [2] by the National Measurement Institutes (NMIs) of the Metre Convention. Currently, the Secretary of the CIPM is preparing another document, addressing more technical considerations on future needs for metrology. The final document should be ready before the next CGPM in 2003 and show the metrological challenges for the next years. The valuable work done at the NMIs and international organizations, e.g. IEC and ISO, where future projects are considered, may be complemented with prospective studies in connection with new emerging technologies. Contributions of the NMIs and CIPM Consultative Committees will be valuable for the elaboration of this new document.

This document represents what is essentially a report on the progress made in compiling information from three NMI's (NPL-UK; PTB-Germany and IEN-Italy) on their views relating to the future requirements for metrology in the area of Acoustics, Ultrasound and Vibration.

2 Rationale

At the Second meeting of the Consultative Committee (CC) for Acoustics, Ultrasound and Vibration, held at BIPM over the period 4-5 October, 2001 an informal working group was formed addressing the likely future requirements for metrology. The grouping consisted of PTB (Germany), IEN (Italy) and the NPL (United Kingdom). Information would be gathered in an informal way with the study findings being disseminated more widely to the CC, through this Draft Report, for comment and input. Views would also be sought more widely from NMI's who did not attend the 2001 BIPM meeting, for example NIST (USA). At the CC meeting, a discussion document was presented by Joaquin Valdés, and this has been included as Annex A of this draft report. Key findings from the Valdés document, which represents a long term vision of the future requirements for metrology, will be assimilated into the main body of the current report.

It was decided very early within the process that the most effective means of gathering information would be through an e-mail based questionnaire. The standard proforma used for this purpose is given in Annex B, and the rationale behind some of the information gathered will be outlined below. This information would in the first instance be summarised in the form of a set of high level topics suitable for consideration in the Robert Kaarls Report. This information was reported to CIPM on 23 April 2002. The variuos parts of the proforma will now be described.

2.1 Summary of current research activities.

This information would establish the areas of research in which the NMI's were currently engaged and to what extent work underpinning work to meet future needs was being carried out.

2.2 Future needs.

Description of project. This information should include a statement related to why this new area of metrology was required, i.e. what was the driver.

Time-scale. Having identified the particular Topic, the recipient of the questionnaire was asked for a very crude estimate of the time-scale over which the particular requirement had to be met. This was split into the following categories: **Short** (< 5 years); **Medium** (between 5 and 10 years) ans **Long** (>10 years).

Resource requirement. The NMI was asked to provide an estimate of the resource required to meet the end requirement, with two categories being used: **High** or **Low**, defined in the following way:

Low resource requirement: The particular topic could, in principle, be addressed by a individual laboratories, although there would be efficiency savings were the work to be addressed through collaboration at regional or inter-regional level.

High resource requirement: The resource requirements to address this topic are probably too great to be addressed by an individual laboratory and collaboration could be a necessity.

Although the time and resource estimates gathered within the questionnaire would be necessarily crude and to some extent subjective, it was felt that such information might would primarily be useful in identifying technical areas in which there would be benefit in a collaborative sharing of effort.

3 Current research activities of the laboratories

Annex C summarises the responses obtained from the NMI's: NPL, IEN and PTB. The format of the information reported was slightly different for the three laboratories but each will be transposed as it appeared on the questionnaire reply.

4 Analysis of responses

The short form list of high level topics derived from questionnaire responses is given in Annex D, where information of the particular Time-scale and Resource requirements are also presented. One immediately obvious feature of the responses is the extensive number of topics identified which span all three technical areas. In this context, it is useful to distinguish between those which involve incremental development of existing capability and those which represent significant new areas of metrology. An attempt to identify the latter areas will be made and these are picked out and amplified in Section 5.

As anticipated, the majority of identified future developments involve the extension of the 'working' range of a particular measurement, for example as a function of acoustic ***frequency***:-

1.3 Calibration of microphones and sound level meters in the frequency range 0.1 Hz to 30 Hz (Airborne acoustics);

2.3 Comparison of hydrophone sensitivity calibrations within the frequency range 15 MHz to 40 MHz (Ultrasonics);

3.5 Development of new tests and calibration methods for impedance heads (frequencies up to 16 kHz) (Acceleration and vibration);

and acoustic ***amplitude***

1.5 Calibration of measurement microphones at high pressure levels (Airborne acoustics);

2.10 Development of methods for characterising the acoustic output of high intensity ultrasonic surgical and therapeutic equipment (Ultrasonics);

3.6 Extension of the range of high-intensity shock calibrations to acceleration peak values up to 1000 km/s^2 (Acceleration and vibration).

The need to test the performance of systems under extreme environmental conditions which are more representative of the use of the particular device is also indicated. Within the underwater acoustics area, there is a need be able to test and evaluate the performance of transducers and hydrophones through applying conditions similar those those under which they will be used, at depth in the ocean, for example, in:-

2.17 Improved acoustic material properties determination under simulated ocean conditions.

2.24 Development of a new generation of reference hydrophones which are stable with temperature and depth.

The key feature of the Valdés report is the prediction of a drive to generating ever smaller transducers, to the point where nano-microphones or nano-hydrophones based on exceedingly novel concepts which potentially could mimic biological systems may develop. This move towards miniaturisation, and the consequent new calibration and characterisation difficulties these developments will provide, is well represented within the NMI responses:-

1.4 Calibration of miniature microphone and microphone arrays fabricated from nano-technologies or (more likely in the shorter term) other emerging technologies (Airborne Acoustics);

2.8 Development of a new generation of ultrasonic hydrophones providing high spatial resolution and wide measurement bandwidth (Ultrasonics);

2.25 Calibration of miniature sensors (Underwater acoustics).

Although the Valdés report does not provide an estimate of the time-scale for these emerging nano-hydrophones or nano-microphones, it is anticipated that this is likely to be greater than 10 years.

It is also crucially important to examine the drivers leading to these metrological requirements. Several anticipated key metrological areas relate to determining human exposure and addressing issues of safety of the individual:-

1.2 Development of primary standards for sound pressure in the frequency range 20 kHz to 200 kHz (Airborne acoustics);

2.2 Characterisation of temperature increase generated by medical ultrasound systems within both phantoms ('in-situ') and tissue ('in vivo') (Ultrasonics);

3.3 Development of new test procedures for the pattern approval for instruments for human response to vibration (Acceleration and vibration).

5 Recommendations – identification of key areas.

As mentioned within the previous section, many of the future developments relate to incremental developments building on existing metrological capability. For these areas, the resource implications may not be too great and the requirements may be able to be met through extending national programmes of work. Clearly, this is a very general statement and each topic area needs to be assessed on its merits. In some areas, simple extension of frequency range, for example, may require significant development in terms of new standards, measurement devices and methodologies. However, the following areas have been picked out as representing key new areas the rationale for which might orignate from a number of areas. It may:-

- require signficant advances in technology before it can be met (devices, systems);

- need a major advance in the understanding of the processes taking place;

- demand a multidisciplinary approach;

- simply be due to the sheer volume of work entailed.

These have been assessed for the areas of Airborne Acoustics, Ultrasonics and Underwater Acoustics and are outlined below.

5.1 Airborne acoustics.

5.1.1 Development of primary standards for sound pressure derived from optical measurements (laser anemometry).

Since the 1960s the reciprocity method has been the foundation of primary standards for sound pressure in air, but before that the Rayleigh disk was used to measure particle velocity and so determine sound pressure. Developments in optical technology now provide the potential to revisit such direct methods. NPL is investigating the use of laser doppler anemometry (LDA) to determine the particle velocity in a freely propagating spherical wave. The relationship between sound pressure and particle velocity in such a field is well-known, so there is potential for direct free-field calibration of microphones by this method (NPL).

Calibration of microphones by means of laser interferometry. This R&D activity could lead to an alternative primary method for the calibration of measurement microphones. Once this development has been settled, it would enable the validity of the reciprocity method to be verified. Furthermore, it could serve as a calibration means which might be easier to handle (PTB).

5.1.2 Development of primary standards for sound pressure in the pressure range 20 kHz to 200 kHz (airborne ultrasound).

There is a rising concern on the effect of sound pressure in air at frequencies above 20 kHz and up to 200 kHz on health. At present, traceability to primary standards is available only up to 25 kHz. No laboratory standard microphone can operate in this frequency range. New laboratory standard microphones need to be developed and a primary calibration method has to be either set up from scratch or an existing one has to be extended to the frequency range of interest (IEN).

An increasing number of applications are resulting in potentially hazardous levels of ultrasound being developed in air. At present there are no measurement standards that cover the frequency range above 50 kHz and international agreement above 20 kHz is not of the level of lower frequencies. There are also few guidelines available on safe levels of airborne ultrasound, but in any case, the measurement standards need to be in place before measurements can be made against any guidelines (NPL).

From PTB: In practice there is a need to perform sound measurements in the range from very low frequencies (0.1 Hz) to very high frequencies (200 kHz). Often the results are intended to decide whether a noise is harmful to the human ear or not. The requirements and test procedures given in the standards, however, are only defined in the frequency range 10 Hz to 20 kHz. Therefore, new requirements and test procedures have to be developed for the extended frequency range.

a. Development of new test procedures for sound level meters in the frequency range 20 kHz to 200 kHz;

b. Development of a suitable test room or environment for the acoustic measurements of clause a), given above;

c. Development of procedures for sound measurements at very high (up to 200 kHz) and very low frequencies (down to 0,1 Hz – see item 5.1.3 given below).

(PTB also indicated a need for measurements over an extended frequency range for both Sound level meters and measurement microphones).

5.1.3 Calibration of microphones and sound level meters in the frequency range 0.1 Hz to 30 Hz.

Pressure reciprocity calibration has traditionally been regarded as having some practical low-frequency limit. DPLA, Denmark have recently reported[1] some success with reciprocity calibrations at very low frequencies, showing that these reservations were held unnecessarily. Further work is perhaps necessary for others to gain similar experience. The problem then is how to transfer these calibrations to working standard microphones and sound level meters to support requirements of IEC 61672 (NPL).

5.1.4 Calibration of miniature microphones and microphone arrays fabricated from nano-technologies or (more likely in the shorter term) other emerging technologies.

New measurement microphones are about to be introduced on the market. Many of them are not only unsuitable for pressure calibrations or other standard methods, but they may exhibit unconventional measurement characteristics (like adaptability to different sound fields etc.) that make comparison calibrations problematic. A study on the impact of these new family of transducers on calibration requirements is the first step to establishing new calibration methods. The driver for this subject is not yet very clear, but as soon as new sound measuring instrumentation will be put into the market there

[1] Report to EUROMET sound-in-air working group, Istanbul 2001.

will be requirements from both manufacturers and organisations for environment protection and health care (IEN). Fabrication of microphones from silicon offers the potential for low cost, small size and manufacturing reproducibility. Once introduced to the mainstream market, their take-up is likely to be extensive. Traditional calibration methods may not be appropriate and alternatives need to be sought ahead of the demand for calibration. This will need to deliver both magnitude and phase information as these microphones will be particularly suited to operation as part of an array (NPL).

5.1.5 Standardised methods for the evaluation of free-field rooms and enclosures and hemi-anechoic rooms.

Free-field rooms are one of the most established tools used in acoustical measurement and testing. It is surprising then, that there are no standardised procedures for their evaluation. A number have been proposed in the past, such as the traditional pressure/distance relationship, but the question of how to present such results is left open. Other methods could be conceived today such as those that consider the impulse response of the room. Further requirements, such as those associated with test boxes could be addressed. Another important detail is the availability of suitable omni-directional sound sources to facilitate testing to the current accuracy requirements. Although the focus here is on free-field rooms, much of the outcome is likely to apply also to hemi-anechoic spaces (NPL).

5.1.6 Evaluation of the performance of ear simulators when used with short duration signals.

At present no standards exist defining test methods or reference levels for audiometric tests using short-duration signals namely auditory brainstem response and otoacoustic emission. Equipment performance is partially defined for auditory brainstem response but not for otoacoustic emission. With the proliferation of different tests there is also a need for the standardisation of methods. As with tympanometer, a problem exists as there are many different physical probe configurations (NPL).

PTB felt that there were extensive requirements in the area of audiometry:-

Development of new or improved test procedures for many different acoustical simulators of the human ear and head are missing or are relevant for only a restricted frequency range.

- ear simulators according to IEC 60318-1 up to 16 kHz;
- occluded ear simulators according to IEC 60711 up to 16 kHz;
- acoustical couplers according to IEC 60318-3 and IEC 60126 up to 8 kHz;
- mechanical couplers according to IEC 60373 up to 16 kHz;
- head and torso simulators (HATS) for sound sources close to the ears.

Determination of the audiometric zero (RETSPLs) on the ear simulators and couplers mentioned in A.4 for new audiometric test signals (for example: test signals of short duration) or new types of earphones.

The ISO has been called upon to determine reference thresholds of hearing for many new test signals intended to determine hearing disorders more correctly.

Development of an universal ear simulator.

At present, for the calibration of the various kinds of earphones (supra-aural, circumaural, concha and insert earphones) and the test of the various types of sound sources close to the ears a series of different ear simulators is required (according to IEC 60318-1, -2, -3; IEC 711; IEC 959; ITU-P 57 etc). An ear-like model should be developed which replaces all ear simulators currently used and which is suitable for the calibration of all earphones available. Once this ear-like model is developed the calibration work could be reduced considerably.

5.1.7 Standardisation of metrics used for sound quality and subjective characterisation of noise.

Increasing use is made of sound quality in assessing acceptability of products which emit sound. We should therefore rationalise and improve the use of sound quality assessment techniques through standardisation of the metrics. This should aim to harmonise definitions of the common metrics (roughness, sharpness, etc.), of methods of measurement, and of methods of hardware/software validation (NPL).

PTB: Auralization of room acoustics, building acoustics and noise exposure.

a. Determination of the discrepancies between the sound quality of real sounds and those of an auralisation with simulation programs. This concerns the sound colour and the localisation of the sound source inside the room. In addition to this the "acoustical wellness" of listeners differs when listening to sounds in a real room or in a simulated room. There does not exist any accepted explanation for this effect.

b. Reproduction of real sound radiation properties of musical instruments by simulation with help of loudspeaker arrays/clusters. This will help to get realistical sounds for a judgement of musical rooms and for better simulation and auralisation results. In addition such a reproduction source will be used as a reference sound source for acustical measurements for room- and building acoustics.

c. The sound distribution in closed rooms depends on the sound reflection on the walls and the radiation pattern of the sound source. That's why it is necessary to consider the sound radiation pattern of the source when calculating the noise assessment or when calculating an auralization in a virtual room. The PTB has started a collection of data such as those for the most important sound sources as e.g. musical instruments.

PTB: Perception - correct assessment of noise. Most of the rated acoustical quantities used today are designed to describe the perception of acoustical signals by human beings. But it is known, that for instance the A-weighted level is not an adequate measure for the annoyance of sound. Similar arguments apply for the weighting curves in building acoustics. It is, therefore, a challenge to develop quantities that reflect the way noise is perceived.

5.1.8 Structure borne sound - description of sources and transmission paths.

Every sound or vibration is transmitted on its way from the source to our body or ears at least partly as structure borne sound. With structure borne sound some simplifications have to be given up, which we are used to with air borne sound. That is why there does not even exist a quantity to describe the strength of vibration sources. Consequently there are vibration test sources in use which are completely mismatched to the measurement task and therefore yield wrong results. The standard tapping machine acc. to ISO 140 is a good example. Also there is no prediction tool yet to estimate the sound pressure level produced by technical equipment e.g. in living rooms in buildings. The task of the project 'structure borne sound' is to define source descriptors which are applicable in practice. It will be necessary not only to gather dynamical characteristics of the sources (like velocities, forces and moments) but also mechanical characteristics (like mechanical source impedances) of the sources and receiving structures. Adequate measurement methods have to be composed. A special point of interest is the fact that in practice sources are fixed to the bearing structure by many points or even areas and not just at one single point. Having enough data, calculation models shall be created to predict noise and vibration from any kind of technical equipment (PTB).

5.2 Ultrasonics.

5.2.1 Development of validated methods of measurement for assessing *'in-vivo'* temperature rises and cavitation occurrence generated by diagnostic and therapeutic medical ultrasonic equipment.

Within the developed world, the majority of foetuses are exposed to at least on diagnostic ulatrsound examination. Bio-effects arising from ultrasound are well established with tissue heating and acoustic cavitation though to be the two primary mechanisms. Currently, the assessment of thermal risk during a diagnostic ultrasound examination is mainly based on thermal index calculations determined from ultrasonic field parameters obtained from measurements in water. Comparisons with both *in-vivo* and phantom measurements show significant differences, in particular when self-heating of the transducer is taken into account. The improvement in measurement based assessment procedures for thermal risk is important for the development of safety guidelines (PTB). This work is required for safety assessment and potential classification of medical diagnostic ultrasound equipment. Thermal Test Objects or phantoms developed to determine capability for diagnostic systems to generate temperature rises require validation against other methods such as MRI or possibly techniques using ultrasound (NPL).

5.2.2 Development of new generation of ultrasonic hydrophones providing high spatial resolution and measurement bandwidth.

Required for characterising the increasingly smaller and higher frequency acoustic beams being used within diagnostic ultrasound in applications such as ophthalmology. Fibre-optic devices hold the promise of meeting these requirements and the attraction of the this type of device is the high spatial resolution and the fact it tends to perturb the applied acoustic field in only a limited way. It may be important to include aspects of calibrations and characterisation of relatively low-sensitivity devices (NPL).

5.2.3 Development of measurement methods for characterising the essential properties of hostile cavitating acoustic fields of the type used in ultrasonic cleaning and sonochemistry.

High power ultrasound is applied in a wide range of industrial applications, where cavitation is normally the agent applied to bring about physical and chemical changes within a medium. No method currently exists for characterising the level or degree of cavitation activity, or any other key properties of this hostile type of acoustic field. The development of such methods would lead to a better understanding of the processes involved and enable them to be monitored, controlled and optimised effectively. This could then be linked into the particular process been applied i.e. cleaning etc (NPL). The characterisation of cavitating fields and the quantitative description of its application in cleaning devices and sonochemistry is still of great interest. Future investigation should focus on the development of sensors providing signals related to the cleaning action (PTB).

5.2.4 Development of methods for characterising the acoustic output of high intensity ultrasonic surgical and therapeutic equipment.

High Intensity Focussed Ultrasound is being applied to destroy cancerous tissues. There is a need to determine the key properties of the acoustic field in terms of output power and spatial-peak intensities, as well as the thermal dose applied to cancerous tissue. Particular measurement issues will again be cavitation and the thermal effects generated by the exceedingly high applied powers and time-averaged intensities. Measurement standard are required for equipment development and the optimisation of treatment regimes (NPL).

5.2.5 Development of standards for acoustic emission.

To date, there has been no traceability for acoustic emission measurements, a technique which is widely used within industry to monitor the condition of safety-critical and production-critical systems such as pressure vessels, engines, high speed machinery etc. Acoustic emission measurements is potentially a very important technology for the future, with industries such as aerospace and pharmaceuticals likely to derive considerable benefit from the availability of traceable measurements.

This includes the ability to transfer results between similar systems, which is not possible at present (NPL).

5.3 Underwater acoustics.

5.3.1 Development of primary standard for free-field sound pressure using optical measurements, including 3-D mapping of acoustic fields.

Traditionally, the primary standard method for free-field calibration of hydrophones (and so realising acoustic pressure standards) has been the method of three-transducer spherical-wave reciprocity. This is an indirect method, which has limitations in overall accuracy. Developments in optical technology now provide the potential to use optical calibration methods which are more direct and have the potential for greater accuracy. NPL is investigating the use of optical methods to determine the particle velocity in a freely propagating spherical wave. The relationship between sound pressure and particle velocity in such a field is well-known, so there is potential for direct free-field calibration of hydrophones (and projectors) microphones by this method. Improved accuracy will give much-needed extra headroom between the primary standard and the secondary dissemination methods and will enable greater accuracy for the most demanding requirements (NPL).

5.3.2 Standards for measurement of underwater radiated noise.

It is recognised increasingly in the off-shore industry that the acoustic noise radiated from underwater platforms such as Remotely Operated Vehicles can seriously limit the performance of acoustic equipment mounted on the platform. For example, the range over which acoustic positioning equipment can provide accurate tracking data is degraded as the self-noise of the platform is increased. Before manufacturers of ROVs can take steps to reduce the radiated noise, an acceptable method of measuring the noise is required. True free-field measurements require a deep-water noise range or a sea-trial, both of which may be prohibitively expensive. However, rapid measurements of radiated noise power are possible in the kinds of reverberant tank often possessed by ROV manufacturers.

It is not yet clear whether such methods have sufficient accuracy to be useful, and work is required to collate data on existing methods and results, assess the requirement for standard rapid methods of measuring radiated noise, and coordinate the efforts in this area, possibly via the IEC where there is already a work item within Technical Committee 87. To be successful, this project requires considerable industrial input and it is envisaged that the project would be strongly collaborative in nature (NPL).

5.3.3 Calibration of velocity hydrophones and sensors, including acoustic intensity sensors.

Velocity hydrophones are now being developed which may be used at frequencies up to a few kilohertz. Typically, these devices would be used in applications such as towed arrays where directional discrimination is required from an essentially linear array. In the future, velocity sensors may be developed further to provide a measurement of acoustic intensity. Calibration methods for velocity hydrophones have been developed at low frequencies using travelling wave tubes. Traceability for such measurements is not yet fully developed and further work may be required to assess the uncertainties in the method (NPL).

5.3.4 Development of standards for Acoustic Doppler Current Profilers.

Acoustic Doppler Current Profilers are commonly used to measure the velocity of a moving vehicle or target, or to measure flow (eg ocean current). Standards for the calibration of such units are not available and work is needed to develop standard calibration methods and specification standards though international standards authorities (NPL).

6 Proposed next steps

This report summarises progress made in assessing future requirements for metrology in the area of Acoustics, Ultrasound and Vibration. Views of experts within the NMI’s of the Germany (PTB), UK (NPL) and Italy (IEN) have been sought. Prior to finalising the report, although general comments and input from the Consultative Committee experts are requested, the following specific input is required:-

- the ‘key’ areas identified in Section 5 should be widened to include Acceleration and Vibration;

- the individual topic areas in Section 5 should be critically assessed to establish whether they do represent the technical areas of metrological importance in the future.

7 References

[1] Besoins nationaux et internationaux dans le domaine de la métrologie. Rapport préparé par le CIPM pour les Gouvernements des Ëtats membres de la Convention du Mètre. 1998 Bureau International des Poids et Mesures.

[2] Reconnaissance mutuelle des étalons nationaux de mesure et des certificats d’étalonnage et de mesurage émis par les laboratoires nationaux de métrologie. Paris, le 14 octobre 1999. Mutual Recognition Arrangement (MRA) for national measurement standards and for calibration and measurement certificates issued by national metrology institutes.

ANNEX A

FUTURE NEEDS FOR METROLOGY IN ACOUSTICS, ULTRASOUND AND VIBRATION

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Introduction.

The CIPM document on National and International Needs in Metrology published in 1998 [1] was a first answer to a mandate given by Resolution 11 of the 20th CGPM in 1995. That report focused the role of the BIPM and the need to improve the international harmonization in measurements, stating the basis for the Mutual Recognition Arrangement signed in 1999 [2] by the National Measurement Institutes (NMIs) of the Metre Convention. Now the Secretary of the CIPM is preparing another document, addressing more technical considerations on future needs for metrology. The final document should be ready before the next CGPM in 2003 and show the metrological challenges for the next years. The valuable work done at the NMIs and international organizations, e.g. IEC and ISO, where future projects are considered, may be complemented with prospective studies in connection with new emerging technologies. Contributions of the NMIs and CIPM Consultative Committees will be valuable for the elaboration of this new document.

The need to develop ever smaller transducer in acoustics.

Concerning the challenges in acoustics, both Jarvis and Nedzelnitzky agree that there is a general need to develop ever smaller transducers, because the effects of difraction caused by practical microphones are usually not negligible [3], [4].

The smallest conceivable objects are now being developed at the nanometer scale in almost every fields of technology, also with applications in acoustics.

Important prospective studies show that nanotechnology is the most likely area of science and engineering to produce the breakthroughs of tomorrow [5].

Some authors mention a famous lecture of Richard Feynman, entitled “There is Plenty of Room at the Bottom” [6], as the first serious reference to the idea of building objects atom by atom. Nevertheles, it was after the invention of the Scanneling Tunneling Microscope [7] and the possiblity to obtain surface images with atomic resolution, that the nanotechnology revolution began. The same tool was used some years later to move individual atoms from one position to another, allowing the building of structures like molecules, quantum corrals, or “nanowires” at the atomic level [8]. This rather cumbersome method is not ideal for mass production. Therefore, scientists are now looking for self-assembling processes where, once designed and launched, atoms and molecules arrange themselves in the programmed manner. New sensors, devices, membranes and biomaterials are being accordingly developed [9] – [11].

The ability of carbon atoms to assemble themselves in particular structures was used to build extremely thin carbon nanotubes, tiny rods with a diameter 10.000 times smaller than a human hair [12]. These hollow cylinders of carbon atoms are already commercially available and can be used in a lot of applications, among others the design of Micro and Nano Electro-Mechanical Systems (MEMS and NEMS), including new types of nanomicrophones.

Life itself seems to be governed by self-assembly codes. This gave origin to the idea of biomimetics, i.e. the formation of nanostructures for new materials and devices designed imitating nature. Even this concept was already mentioned by Feynman in his lecture, as he wrote, referring to the marvelous biological system: “A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things, all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want, that we can manufacture an object that manoeuvres at that level!”

Understanding better the structure and function of the human ear may stimulate the fabrication of nonbiological nanomicrophones. In return, the fabrication of nanomicrophones can provide tools for exploring the interior structure and functions of cells.

The cochlea is a very complex mechanical apparatus, which includes in a small volume an acoustical amplifier and a frequency analyzer. The sensing elements in the hair cells are stereocilia, which have diameters of the order of tens of nanometers and a large length compared to their small diameters. Carbon nanotubes may have diameters and aspect ratios comparable to biological stereocilia, but also high strength and extreme sensitivity to very small strains.

What is amazing for metrologists, always searching for the limits of measurable effects, is that the human ear is capable to detect fainter sounds displacing stereocilia by only fractions of a nanometer. The threshold of hearing occurs indeed for a cilium deflection of only 0.003 degrees. The random noise due to Brownian motion in the endolymphatic fluid is reduced by the fact that stereocilia move as a bundle for concerted action [13].

Based on bio-inspired nanosystems, Flavio Noca and co-workers at the Jet Propulsion Laboratory (NASA) came to the idea of building a dense bundle of artificial stereocilia with carbon nanotubes arrays, in principle for detecting swimming micro-organisms, revealing the presence of life in other planets. By working out some numbers, they found that flat acoustic membranes would never do the job of sensing nanoscale movements. The use of carbon nanotubes arrays, bridging nanoelectronics with biology, should give rise to a novel nanomicrophone. Although membrane-based approaches to directional sensing of sound waves are also being developed, Noca is of the opinion that cilia microphones will be better, because the miniaturization of conventional acoustic sensors is limited by the increasing stiffness of membranes as the size is reduced. Membranes are present in the cochlea only as coupling devices between the acoustic environment and the zone, but Nature has evolved toward stereocilia, probably because of their unique properties at very small scales. The main ideas were presented on December 2000 during a meeting of the Acoustical Society of America [14], and some previous results are expected to be published by the end of 2001.

Several applications are envisioned, e.g. to test water quality or monitor the activity of living cells (nanostethoscope), distinguishing cancerous cells, which are known to have a more intense activity, from healthy cells.

Other authors are also looking for medical applications, studying the hair cell's transducing mechanism from the biochemical point of view. The neuroscientist Peter Gillespie at the John Hopkins University intends to describe the mechanical chain of proteins that links one stereocilia to another. He believes that within 10 years, hair cell regeneration strategies are going to emerge [15].

As those studies are also carried out looking for future aquatic research in space, the bio-inspired technology of carbon nanotubes arrays will provide a miniature acoustic sensor working in air or under water. Therefore, also nanohydrophones could be perhaps conceived by metrologists, with the advantage that instead of needing water tanks to test their performance, a water drop could be sufficient.

Carbon nanotubes arrays functioning as actuators instead of sensors will be capable of generating acoustic signals for applications in active acoustic instruments such as sonar and sodar (sonic detection and ranging) arrays, acoustic systems that measure turbulence and wind speed in the atmosphere. Hence, one could also imagine the application of those nanomicrophones sensing and emitting signals in order to calibrate themselves by the same way as it is usually done with the reciprocity method. Nevertheless, carbon nanotubes may be not suitable for building a standard microphone before solving, among other problems, some questions related to electrical noise. It is already known that they may present a pronounced 1/f noise, so as it happened with carbon microphones. In fact, the noise magnitude in carbon nanotubes greatly exceeds that commonly observed in metal films, carbon resistors, or even carbon fibers with comparable resistances [16], [17]. We should then also look for other possible solutions, perhaps at the interface between acoustics and heat.

A new intriguing area is that of phonon counting. With integrated nanoscale thermal transducers it appears feasible to perform calorimetric measurements providing access to the domain of individual thermal phonons transport (yoctocalorimetry) [18].

Other efforts are devoted to generate and detect single phonons with mechanical devices at the quantum limit, where vibrational quanta become evident, using nanometer scale mechanical resonators, electromagnetically driven, developed by Cleland and Roukes [19], [20]. Sensing is intended via two different ways, one attempt uses a single electron transistor, the other is based on the Josephson effect in superconducting tunnel junctions. The authors do not yet know whether they will be able to observe quantized amplitude jumps. The hope is that single phonon generation and detection could be accomplished in 1 or 2 years, at frequencies around 0.1 to 1 GHz and very low temperatures. In that case one may imagine nanoscale resonating devices emitting and detecting calculable energies, which could be in turned received by artificial stereocilia nanomicrophones, although at frequencies higher than those corresponding to the acoustical range. Energy coming in the form of heat could also be in principle measured, because stereocilia have the capability of sensing signals below the noise levels due to Brownian motion, the fluctuations due to heat. Perhaps the old idea of the thermophone could be revisited by metrologists in the near future at the nanoscale domain.

Miniaturization in the field of vibrations and economical impact.

Miniaturization is also becoming important in the field of vibrations with the development of new MEMS, including accelerometers and seismometers. Smart piezoelectric accelerometers with wireless interface for industrial applications are being developed, containing built-in microprocessors, associated amplifier and radio circuitry for signals emission once incorporated, for instance, in rotating electric machinery or aircrafts. This enables vibration sensors with greatly enhanced capabilities. Failures prediction with continuously monitoring vibrations equipment can decrease downtimes, which in the case of the pulp and paper industry may cost 1 million US$ per day. Savings from installation worldwide of such devices for machine maintenance and monitoring were calculated at 500 million US$ within the frame of a NIST Advanced Technology Project [21].

Car airbags also provide a good example of how the cost of technology is decreasing, while functionality is increasing, because the accelerometer trigger they content can now be built on a single chip that is not only cheaper but smarter and more reliable [22].

The Center for Space Microelectronics Technology at the Jet Propulsion Laboratory (NASA) is developing a suite of miniature seismometers and accelerometers for planetary and microgravity science. The JPL Prototype Mars seismometer is an ultrasensitive instrument in a robust, compact, and low-power package. A sensitive capacitive displacement transducer measures the deflection of a 3g proof mass with a sensitivity better than 10^{-9} g / $Hz^{1/2}$ and bandwidth of 40 Hz for vertical acceleration [23].

Telemetrology.

Communications between metrologists participating in key comparisons are normally done by fax and e-mail. In the last years a communication network of computers created at NIST, operating through the Internet, began to be used within the Interamerican Metrology System SIM (Sistema Interamericano de Metrología) [24]. This new communication technology, particularly usefull for electrical comparisons, may also find application in those key comparisons stated by the CCAUV, and also in future remote calibrations within the frame of the national and regional calibration services activities.

Uncertainty in measurements and 1/f noise.

Standards maintenance is made by repeated measurements over long periods of time. In the presence of low-frequency noise, the longer the observation time, the greater the measurement uncertainty. In the case of atomic time standards, where the power spectrum analysis indicated that fluctuations are of the 1/f type, the Allan variance began to be early used for uncertainty calculations instead of the classical variance [25].

Similar long term fluctuations were later observed associated with different standards, such as voltage standard cells, Thomas-type wire wound standard resistors, stainless steel mass comparisons [26] and more recently in voltage transfer standards based on Zener diodes [27]. Nevertheless, in all these fields remains the classical variance being used for the calculation of the uncertainty.

A revival of this question seems to appear now in the metrological community, after the signature of the MRA by most of the countries within the Metre Convention. This happens in connection with discussions in the CIPM Consultative Committees meetings, in order to determine the reference value and properly assign the uncertainty to the degree of equivalence, i.e. the deviation of each laboratory participating in key comparisons from the corresponding reference value. Particularly in the CCEM, the Consultative Committee for Electricity and Magnetism, a contribution paper is being presented as a working document [28], with possible implications for the other CIPM Consultative Committees. The authors show that, in the case of white noise processes, one should better compare each reported value with the average of the others, instead of assuming a single comparison reference value given by the arithmetic or weighted mean of all the results. Moreover, when the artifact noise is not purely white, the laboratories measuring in the middle of the comparison may be in a considerable better position than those measuring at the beginning or at the end of the comparison. This should apply to 1/f noise and especially to $1/f^2$ noise.

It seems to be that in the future fundamental metrology, the usual practices for reference values and measurement uncertainties calculation using the classical variance will be quite different in most fields of metrology, including possibly also the field of acoustics, ultrasound and vibrations.

Acknowledgement.

I greatfully acknowledge to Andrew Cleland and Flavio Noca the information provided concerning their on-going results and their hopes for the future.

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ANNEX B

FUTURE NEEDS IN ACOUSTICS, ULTRASOUND AND VIBRATION

Reporting scheme designed for data compilation.

1 SUMMARY OF CURRENT RESEARCH ACTIVITIES.

A brief overview required.

2 FUTURE NEEDS.

2.1 Technical area

(Note 1: Acoustics, Ultrasound or Vibration).

2.2 Title of topic.

2.3 Short description of the subject.

(Note 2: this should also include a short statement of the requirement driver i.e. is the work needed to meet an industrial or societal need).

2.4 Time-scale.

(Note 3: It is suggested that estimates for the time-scale be divided into the following categories: **S**hort (<5 years); **M**edium (between 5 and 10 years) and **L**ong (greater than 10 years)).

(Note 4: A very crude estimate of the resource requirement should be given in the following two Categories: **LOW** or **HIGH**.

For the purposes of this information gathering exercise, the following definitions of these terms are used:-

Low resource requirement: The particular topic could, in principle, be addressed by a individual laboratories, although there would be efficiency savings were the work to be addressed through collaboration at regional or inter-regional level.

High resource requirement: The resource requirements to address this topic are probably too great to be addressed by an individual laboratory and collaboration could be a necessity.

2.5 Suggested action.

Space provided to provide (optional) additional comments.

Prepared for the BIPM Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV).

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ANNEX C

This Annex summarises the responses of the NMI laboratories, when asked to outline their current reserach activities.

C.1 National Physical Laboratory (United Kingdom)

C.1.1 **Technical area**: *Airborne Acoustics*.

- Preliminary research to identify optical measurement methods suitable for use as primary standards for sound pressure

- Development of FE models of laboratory standard microphones

- Improved free-field reciprocity calibration of laboratory standard microphones in the frequency range 1 kHz to 50 kHz

- Use of MLS techniques in secondary free-field calibration of microphones

- Research to support the development of Standards for measurement microphones

- Development and appraisal of methods of evaluating the acoustical performance of free-field rooms suitable for proposal to ISO as a new work item in the future

- Research to determine the combined response of sound calibrators, microphones and sound level meters when the components are sourced from different manufacturers.

- Research to support the development of Standards for sound level meters

- Development of improved method of calibrating artificial ears

- Development of improved method of mechanical couplers

- *Research to support the development of Standards for ear simulators*

- *Development of FE models of ear simulators*

- *Development of methods of measuring short-duration stimuli used in the measurement of hearing*

- *Development of methods of measuring the output of probes inserted in the ear for the measurement of hearing*

- Research to determine the effect of environment, measurement configuration and to evaluate repeatability, to enable full uncertainty budgets to be given in ISO Standard for sound power.

• Research to determine the uncertainty due to the acoustical characteristics of the measurement site (indoor and outdoor) in the measurement of machinery noise

• Research to investigate the use of sound quality metrics and the potential for their standardisation

• Research to evaluate methods of providing a primary reference facility for acoustic emission measurements

C.1.2 **Technical area**: *Underwater Acoustics*.

• Development of optical measurement methods suitable for use as primary standards for free-field acoustic pressure and hydrophone calibration

• Improved near-field techniques for high kilohertz frequencies.

• Improved acoustic material properties determination at ocean conditions (echo reduction and insertion loss)

• Determination of dynamic bulk modulus of materials at ocean conditions.

C.1.3 **Technical area**: *Ultrasonics*.

• Establishment of new NPL primary standard interferometer and validate performance up to a frequency of 60 MHz.

• Establishment of a relative phase calibration service for hydrophones covering the frequency range 1 to 20 MHz.

• Development of a low-cost, easily applied means of providing physiotherapists with traceable ultrasonic power measurements by developing a solid-state power meter.

• Complete implementation and dissemination of the developed membrane hydrophone-amplifier model.

• Develop, evaluate and commission new 0.1 mm and 0.2 mm active element hydrophones for use in the acoustic output measurement service.

• Establishing a measurement facility for determining propagation speed in liquids with an uncertainty of ± 0.2 m s^{-1} or better.

• Enhancing of the capability of the reference ultrasonic cleaning vessel facility.

• Investigating potential calibration techniques for newly developed sensors.

•Undertaking feasibility study investigating potential of new cavitation sesnors in assessing cleaning effectiveness.

C.2 IEN (Italy)

C.2.1 **Technical area**: *Airborne acoustics*.

The Acoustics Department of IEN carries out activity in the field of applied and physical acoustics, the main interest being the realisation and maintenance of the national standard of sound pressure, its direct application to acoustic measurements, and the development of acoustical measurement techniques for the characterisation of thermodynamical properties of fluids.

The national standard of acoustic pressure is realised by the primary method of pressure reciprocity calibration of microphones, and an improved indirect measurement of the acoustical impedance of laboratory standard microphones, recently developed, allows an improvement in the calibration uncertainty.

An experimental apparatus for precision measurement of speed of sound in gases, based on the spherical resonator technique, has been build and tested, achieving an overall relative accuracy in the order of 5 ppm. It is applied to the determination of several thermophysical properties of pure gases and mixtures. At present, measurement capabilities are being extended to speed of sound in liquid at high pressures, so having the possibility to determine with high accuracy heat capacity and isoentropic compressibility in the liquid phase.

C.2.2 **Technical area**: *Airborne acoustics*.

A new activity is starting concerning the measurement of ultrasonic power of transducers based on the radiation force method, according the standard IEC 61157.

C.3 Physikalisch-Technische Bundensanstalt (Germany)

C.3.1 **Technical area**: *Airborne Acoustics*.

Calibration of WS3 microphones for air-borne ultrasound: Ultrasonic devices are increasingly used in many areas of application such as: ultrasonic cleaning, medical surgery, building constructions, traffic and directional loudspeakers. In all these cases air-borne ultrasound may cause harmful effects to workers, surgeons and listeners. A precondition for the jugdement of the danger to people is the correct measurement of the sound field in question. For this purpose a suitable calibration technique for WS3 microphones has to be developed. PTB is about to start such a research project.

Determination of room-acoustical parameters.

a) Exact definition and measuring of the scattering coefficient δ or *s* of wall and absorber structures. There are discrepances in the standards of AES and ISO and only the ISO definition is suitable for roomacoustical simulation. For the practice it is necessary to develop a new or better measurement method for the scattering coefficient.

b) Development of new and improved methods for the measurement of the absoption coefficient α as a function of sound incidence under different angles.The common used method of measuring the absorption coefficient in the diffuse soundfield in a reverberation room is far from the practical need, where the sound insulation depends on the distribution of absorbers in the room.

c) Initiation of methods to measure the absorption and scattering coefficient of arbitrary absorbers in situ for getting suitable data for room simulation programs. The round robins of 1.401 have shown that there are no applicable methods available.

d) Collecting and measuring the sound radiation of musical instruments and combinations for room acoustical simulation and auralisation.

Qualification of reverberation rooms

Reverberation rooms are used for sound power determinations and for the determination of the sound absorption coefficient. When the latter measurement is carried out, the presence of the absorbing material reduces the diffusity. Since a high diffusity is an essential precondition for the underlying theory, there arises a contradiction. At PTB, two different paths are followed for solving this problem. At first, a measurement method for the determination of the diffusity is developed and, secondly, a reference absorber is produced which can be used for a round robin and whose absorbing properties can be calculated analytically.

Impedance and angle error in sound power determinations via the sound pressure enveloping method

In the measurement procedures currently used, the impedance and angle errors are neglected which leads to systematic deviations between sound powers determined by the intensity and by the sound pressure method. As a first step towards a general solution of that problem, PTB is investigating analytically and experimentally the impedance and angle error for model configurations.

Impedance of a walking person

Impact noise is one of the crucial problems in building acoustics. When it is measured, a walking person is simulated by a tapping machine. But the tapping machines currently used have an impedance which distinguishes very much from the impedance of a person. Therefore, the amount of sound power transmitted into the structure under test is incorrect and measurement results can be misleading. To improve the comparability between measurement results and the sound generated by a walking person, PTB is now investigating the impedance of persons and possible modifications of the tapping machine.

C.3.1 Technical area**: *Ultrasound.***

Development of hydrophones with high spatial and time resolution

For the measurement of high frequency ultrasound fields sensors with high spatial and time resolution are urgently needed. Since a number of years PTB is active in the development of optical multi-layer sensors for this purpose. Recent publications give detailed information [1,2].

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Improvement of the lateral resolution of hydrophones by means of deconvolution

In many ultrasound applications conventional sensors and particularly piezoelectric hydrophones do not comply with the requirements for „point receivers“. This is particularly valid for high frequency applications (>10 MHz) in the field of medical diagnostic ultrasound. In the scope of a project PTB developed methods which allow ultrasonic fields to be reconstructed from the spatially averaged measurement values with the necessary resolution [1]. The results obtained are promising and have shown that the lateral resolution of commercial hydrophones can be essentially improved.

Development of transfer standards for ultrasound power measurement

Although physiotherapy with ultrasound is widely used many devices do not comply with relevant standards. The characterization of physiotherapy machines requires practical and reliable measurement procedures and equipment. Scope of current research activities in PTB is the improvement of the well known radiation force measurement technique to cover the high power range necessary for physiotherapy machines. This knowledge will be exploited in a project with European partners.

Calibration in the frequency range 15- 40 MHz

To improve the spatial resolution of ultrasonic imaging the working frequency of diagnostic ultrasound devices in medicine and technology has been permanently increased for the last 20 years. In addition, techniques like tissue second harmonic imaging point to the increasing importance of high frequency range. In the last years PTB has developed a primary standard for hydrophone calibration between 15 and 40 MHz which will be permanently improved.

C.3.1 **Technical area**: *Acceleration and vibration*

Current research activities of the PTB in the area Acceleration & Vibration are part of a long-term program which started more than a decade ago and is going on to realize and disseminate the units and associated scales of the quantity of acceleration and of derived motion quantities, to respond to the increasing needs from industry and other areas. The translational motion quantities acceleration, velocity and displacement, and the rotational motion quantities angular acceleration, angular velocity and rotation angle as well, are to be generated and highly accurately measured at sinusoidal, shock-shaped and other, user-defined time dependencies. Moreover, to simulate during calibration of any transducer and instrumentation the conditions of application (e.g. in calibration laboratories or under manifold field conditions) as closely as possible, special facilities for simultaneous multi-component generation and measurement of the motion quantities at adequate time histories (deterministic or random) have been developed, and will be further developed and exploited.

1.) Design, manufacture and investigation of linear and angular acceleration exciters

To generate motion quantities at sinusoidal and shock-shaped time histories in a single desired degree of freedom, special air-borne exciters have got developed so far at the PTB Section Acceleration as follows:

- Low-frequency acceleration exciter (sinusoidal motion, 0,1 Hz to 20 Hz, acceleration amplitude max 2m/s², displacement amplitude max. 0,5 m)
- Medium-frequency acceleration exciter (10 Hz to 5 kHz)
- High-frequency acceleration exciter (10 Hz to 20 kHz)
- Shock acceleration exciter (50 m/s² to 5000 m/s²)
- Angular acceleration exciter (0,3 Hz to 1000 Hz)

For high shock intensities, a special

- High-intensity shock acceleration exciter (1 km/s² to 100 km/s²), based on wave propagation in long thin bars, has got developed.

Current research and development work *in the field of generation of motion quantities is aimed at:*

- extending the frequency range of generation of rectilinear motion up to 20 kHz (suppressing more efficiently lateral and rocking motion encountered in conventional vibration exciters in the kHz range); the need for even higher frequencies is taken into account in **III C**,
- extending the capabilities of generation of rotational motion quantities to higher frequencies up to 1,6 kHz and to constant angular velocities, respectively (including angular vibration at the rotating state with constant angular velocity).

2) Design, manufacture and investigation of methods and techniques for highly accurate measurement of translational motion quantities

So far, measurement methods and techniques (laser interferometry) have been established which cover the operational ranges of the exciters specified in **1)**.

Current research and development work in the field of interferometric measurement of translational and rotational motion quantities is aimed at:

- extending the ranges of measurement of the motion quantity parameters (i.e. amplitude of sinusoidal motion quantities and peak value of shock acceleleration), e.g. displacement amplitudes down to 10 nm at frequencies below 1 kHz (at higher frequncies, 1 nm has already been achieved)
- further improving the accuracy (relative expanded uncertainty for k = 2 is aimed at 0,1% for amplitudes of sinusoidal motion quantities and
  0, 3% for peak values of shock-shaped accelerations at reference conditions).

3) Simultaneous multi-component excitation and measurement of motion quantities

Recently, a special triaxial acceleration exciter and a special exciter for rotational motion quantities have been developed by the PTB Acceleration Section in co-operation with a consortium of firms from different countries. The acceleration exciter for the orthogonal *X*, *Y*, *Z* components has been equipped with multi-component laser interferometry. The main specifications of the equipment are:
simultaneous triaxial acceleration up to 100 m/s², 1 Hz to 1 kHz; rotational motion quantities from 0,1 Hz to 1 kHz at sinusoidal motion quantities: 1 rad/s² to 1400 rad/s²; shock-shaped, noise and special, user defined time histories can be arbitrarily chosen; rotating state up to 1700 revolutions per minute; calibration temperature range -40°C to 105°C

Current research and development work in the field of multi-component generation and measurement is aimed at:

- Combination of the translational tri-axial exciter with the rotational exciter, establishing laser interferometry for the fourth motion component (rotational), too.
- Completing and optimizing the system to achieve a 4-component acceleration standard measuring device,
- Investigation of the potential measurement capabilities of this multi-component acceleration standard, including the separate application of the air-borne rotational exciter with associated laser interferometer.

4) Realization and dissemination of the units, and the associated scales, of acceleration, angular acceleration and derived motion quantities of solid bodies

In order to realize the unit (and associated scale) of acceleration, for instance, an acceleration exciter (cf. 1) in conjunction with a laser interferometer (cf. 2) - both mounted on a specially developed vibration isolation system - and with some other associated sub-systems (supply, computer etc) are needed. However, as such a standard measuring device would only allow measuring instruments to be calibrated, the standard measuring devices (national standards) developed at the PTB contain, in addition, systems for measuring electrical output quantities of transducers and measuring chains. Consequently, the standard measuring devices are applied to:

- Primary vibration & shock calibration of reference standard transducers, measuring chains and measuring instruments (e.g. laser vibrometers),
- Identification of the dynamic behaviour and calibration of transducers, measuring chains and measuring instruments for translational and rotational motion quantities,
- Selected fundamental metrological investigations of vibration and shock calibrators, transducers, measuring chains and measuring instruments (e.g. investigation of characteristics of reference standard laser vibrometers under development)

5) Development, investigation and application of special measurement facilities

To exploit the potential measurement capabilities of the standard measuring devices (i.e. 7 national standards developed so far), special measurement arrangements have been developed in addition.

Current research and development work in this field is mainly aimed at highly accurate measurement of the phase shift of motion quantity transducers, investigation of special disturbing influences in reference standard transducers and establishing a standard device for the electrical calibration of interferometer signal measuring systems.

ANNEX D

High level listing of metrology topic areas likely to be of importance in the area of Acoustics, Ultrasound and Vibration. Crude estimates of the time-scale of the requirement and the resource implications, are included - see Section 2).

Technical area: Airborne acoustics

1.1 Development of primary standards for sound pressure derived from optical measurements (laser anemometry). **Time: Medium; Resource: Low.**

1.2 Development of primary standards for sound pressure in the frequency range 20 kHz to 200 kHz (airborne ultrasound). **Time: Medium; Resource: Low (NPL). Time: Medium; Resource: High (IEN).**

1.3 Calibration of microphones and sound level meters in the frequency range 0.1 Hz to 30 Hz. **Time: Medium; Resource: High.**

1.4 Calibration of miniature microphones and microphone arrays fabricated from nano-technologies or (more likely in the shorter term) other emerging technologies. **Time: Short; Resource: Low (NPL). Time: Long; Resource: High (IEN).**

1.5 Calibration of measurement microphones at high sound pressure levels. **Time: Short; Resource: Low.**

1.6 Standardised methods for the evaluation of free-field rooms and enclosures and hemi-anechoic rooms. **Time: Medium; Resource: High.**

1.7 Evaluation of room acoustical and noise software. **Time: Short/Medium; Resource: Low.**

1.8 Auralization of room acoustics, building acoustics and noise exposure. **Time: Short/Medium; Resource: Low.**

1.9 Re-evaluation of the audiometric zero. **Time: Medium; Resource: High.**

1.10 Evaluation of the performance of ear simulators when used with short-duration signals. **Time: Short; Resource: High.**

1.11 Development of a universal ear simulator. **Time: Short; Resource: Low.**

1.12 Requirements for ear simulators of neonates. **Time: Medium; Resource: High.**

1.13 Investigation of environmental influences on audiometric earphones. **Time: Short; Resource: Low.**

1.14 Development of testing hearing aids with complex digital processing capabilities. **Time: Medium; Resource: High.**

1.15 Direct force calibration of impedance heads. **Time: Medium; Resource: Low.**

1.16 Improve understanding of the performance of mechanical couplers and their calibration. **Time: Short; Resource: High.**

1.17 Standardisation of room acoustics metrics. **Time: Medium; Resource: Low.**

1.18 Standardisation of metrics used for sound quality and subjective characterisation of noise. **Time: Medium; Resource: Medium.**

1.19 Standardisation of metrics and models used for noise prediction and mapping. **Time: Medium; Resource: Medium.**

1.20 Evaluation of uncertainties in environmental noise measurement. **Time: Medium; Resource: High.**

1.21 Evaluation of uncertainties in sound power measurement. **Time: Medium; Resource: High.**

1.22 Harmonisation of product noise labelling. **Time: Medium; Resource: Low.**

1.23 Development of an active acoustic room suitable for the presentation of natural sound fields and events for improved calibration services. **Time: Long; Resource: High.**

1.24 Damping effects in acoustics - basic research and systematic application. **Time: Medium; Resource: High.**

1.25 Structure borne sound - description of sources and transmission paths. **Time: Medium; Resource: High.**

1.26 Perception - correct assessment of noise. **Time: Medium; Resource: Low.**

Technical area: ULTRASOUND (including Underwater Acoustics)

Ultrasonics

2.1 Investigation of the accuracy of measurements of ultrasonic power under realistic measurement conditions, including converging or diverging ultrasonic fields. **Time: Medium; Resource: High.**

2.2 Characterisation of temperature increase generated by medical ultrasound systems within both phantoms (*'in-situ'*) and tissue (*'in vivo'*). **Time: Short; Resource: High.**

2.3 Comparison of hydrophone sensitivity calibrations within the frequency range 15 MHz to 40 MHz. **Time: Short; Resource: Low**.

2.4 Development of therapy-level ultrasonic power transfer standards. **Time: Short; Resource: Low**.

2.5 Development of calibration methods for the phase response of ultrasonic hydrophones. **Time: Short; resource: Low**.

2.6 Development of validated methods of measurement for assessing 'in-vivo' temperature rises and cavitation occurrence generated by diagnostic and therapeutic medical ultrasonic equipment. **Time: Medium; Resource: High**.

2.7 Development of measurement devices and methods for determining the radiated acoustic power generated by low frequency ultrasonic systems (20 kHz to 50 kHz). **Time: Short: Resource: Low**.

2.8 Development of new generation of ultrasonic hydrophones providing high spatial resolution and measurement bandwidth. **Time: Medium; Resource: High**.

2.9 Development of measurement methods for characterising the essential properties of hostile cavitating acoustic fields of the type used in ultrasonic cleaning and sonochemistry. **Time: Medium; Resource: High.**

2.10 Development of methods for characterising the acoustic output of high intensity ultrasonic surgical and therapeutic equipment. **Time: Medium; resource: Low**.

2.11 Development of methods for determining cavitation dose, both for the area of diagnostic ultrasound and industrial equipment. **Time: Long; Resource: High.**

2.12 Development of simple methods of ultrasonic testing appropriate at the industrial or user level. **Time: Short: Resource: Low.**

2.13 Development of standards for acoustic emission. **Time: Long; Resource: Medium.**

2.14 Improvement of the lateral resolution of hydrophones by means of de-convolution. **Time: Short; resource: Low**.

Underwater Acoustics

2.15 Development of primary standard for free-field sound pressure using optical measurements, including 3-D mapping of acoustic fields. **Time: Long; Resource: High.**

2.16 Improved near-field measurement techniques for high kilohertz frequencies. **Time: Medium; Resource: Low.**

2.17 Improved acoustic material properties determination under simulated ocean conditions. **Time: Medium; Resource: Low.**

2.18 Determination of dynamic bulk modulus of materials under ocean conditions. **Time: Medium; Resource: High.**

2.19 Development of standards for low frequency calibrations from 10 Hz to less than 1 Hz. **Time: Medium; Resource: Medium.**

2.20 Development of standards for the phase response of hydrophones. **Time: Medium; Resource: Low.**

2.21 Standards for measurement of underwater radiated noise. **Time: Short; Resource: Low.**

2.22 Development of new standards for free-field transducer calibration at kilometre depths. **Time: Medium; Resource: High.**

2.23 Calibration of velocity hydrophones and sensors, including acoustic intensity sensors. **Time: Medium/Long; Resource: Medium.**

2.24 Development of new generation of reference hydrophones which are stable with temperature and depth. **Time: Medium; Resource: High.**

2.25 Calibration of miniature sensors. **Time: Long; Resource: High.**

2.26 Development of standards for acoustic Doppler current profilers. **Time: Medium; Resource: Medium.**

2.27 Establishment of a new deep water calibration and testing facility. **Time: Long; Resource: High.**

Technical area: Acceleration and Vibration

3.1 Investigation and calibration of transducers for motion quantities. **Time: Medium.**

3.2 Investigation of motion quantity transducers and mechanical structures using multi-component motion excitation. **Time: Medium.**

3.3 Development of new test procedures for the pattern approval of measuring instruments for human response to vibration. **Time: Medium.**

3.4 Development of calibration methods and test procedures for laser vibrometers (reference standards in particular). **Time: Medium.**

3.5 Development of new test and calibration methods for impedance heads (frequencies up to 16 kHz). **Time: Medium.**

3.6 Extension of the range of high-intensity shock calibrations to acceleration peak values up to 1000 km/s^2. **Time: Long.**

3.7 Extension of the range of angular acceleration calibration to amplitudes up to 50,000 rad/s^2. **Time: Long.**

3.8 Extension of the frequency range of calibration and measurement facilities for sinusoidal motion quantities up to 100 kHz (for calibration and investigation of laser vibrometers in particular). **Time: Long.**

3.9 Realization and dissemination of constant accelerations at high intensities up to 100 km/s^2 (air-borne centrifuges). **Time: Long.**

3.10 Establishment of metrogical prerequisites for ensuring traceability of navigation sensors (calibration and investigation of their dynamic behaviour). **Time: Long.**

3.11 Establishment of calibration and measurement capabilities using low motion quantity intensities, e.g. accelerations down to 10^{-5} m/s^2, at very low frequencies (e.g. for seismic investigations and gravimetry). **Time: Long.**

3.12 Computer-aided simulation of special measurement and calibration processes (standard measuring devices in primary and secondary calibration laboratories included) based on metrological fundamental investigations. **Time: Long.**