Acoustical Metrology at the UK National Physical Laboratory (NPL) 2016-2017

1 Introduction to Acoustic Metrology at NPL

This short report provides an update on the research topics related to Acoustical Metrology currently being undertaken at the National Physical Laboratory in the United Kingdom

The work within the Ultrasound and Underwater Acoustics Group is part of a larger UK-government funded metrology programme. NPL is wholly owned and operated by the UK Government, and is part of the Department of Business Energy and Industrial Strategy (BEIS).

The principal objectives of the NPL work are to:

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

The programme is composed of two principal thematic technical areas dealing with measurement standards. These Themes are:

Standards for Medical Ultrasound
This theme covers standards for medical ultrasound, providing for: the realisation of standards of acoustic pressure and power at acoustic frequencies greater than 1 MHz; the calibration of hydrophones, ultrasonic power meters and measurement of the acoustic output of medical ultrasonic equipment; standardised measurements of tissue heating caused by medical ultrasound; and measurements of cavitation relevant to medical ultrasound.

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, underwater acoustical systems and materials, including calibration at hydrostatic pressures and temperatures corresponding to real ocean conditions; development of standards for in-situ measurement of noise in the ocean.

Changes to the NPL Acoustics Metrology Programme in 2016

In 2016, NPL Management made the decision to close down some of the mature metrology areas within NPL in order to focus available funding on new strategic areas which align with stated funding priorities for UK Government. As a part of this process, NPL Management closed down the work in the area of Sound-In-Air metrology. Therefore, NPL no longer maintains primary standards for airborne acoustics, nor does NPL disseminate standards to the UK acoustics community, and NPL no longer contributes to the international metrology community in the field of airborne acoustics. There has also been a reduction in the scope of the work undertaken in the field of industrial ultrasound. The functioning team within NPL is now called the

Ultrasound and Underwater Acoustics Group, with NPL remaining highly active in the fields of medical ultrasound and underwater acoustics.
From the very inception of CCAUV, the contribution of NPL to the metrology of sound in air has been considerable, with NPL piloting numerous key comparisons and playing a significant role in CCAUV and its various working groups. It is the hope of the NPL staff that the excellence of the expertise and capabilities for airborne acoustic metrology demonstrated by other NMIs will enable the work of CCAUV to continue unabated, and that the effect of NPL's withdrawal will be minimised.

Note that with the departure from NPL of Richard Barham, his place as Chair of EURAMET TC-AUV has been taken by Stephen Robinson.

2 Underwater Acoustics

NPL has a range of capabilities in the field of underwater acoustic metrology, and these are based around several key facilities used to realise and disseminate standards for underwater acoustics:

- two laboratory tanks with precision positioning systems for free-field calibration;
- acoustic pressure vessel (APV) for simulating ocean conditions in the laboratory;
- open-water test facility (OWTF), a floating laboratory located on a reservoir;
- low frequency pressure calibration facilities for hydrophones.

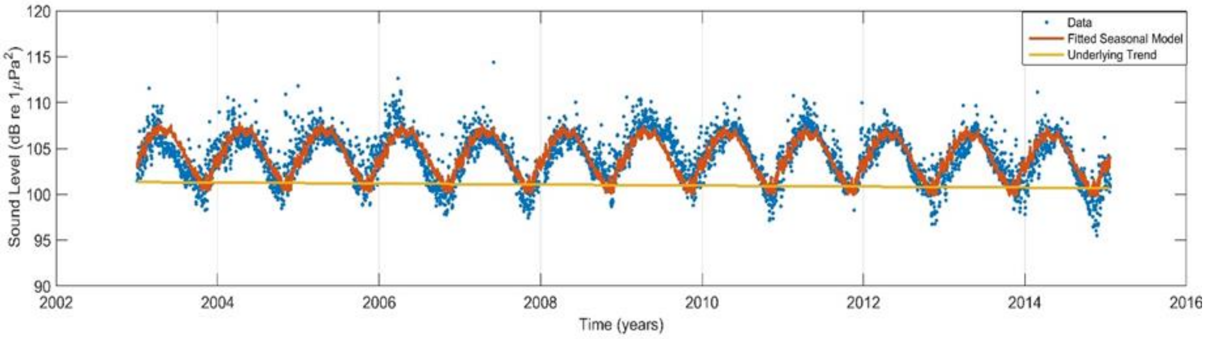
Measurement services, which are accredited to ISO17025, provide underpinning support for UK manufacturing industry – the UK has around 30 companies involved in manufacturing transducers, hydrophones and systems for sonar, positioning, navigation, surveying, communication, weapons and monitoring marine life. NPL also provides traceability for environmental noise measurements, and support for offshore energy and oceanographic applications (NPL has an additional 30 customers and collaborators in the UK end-user community).

In the last two years, NPL has continued its contribution to the development of the metrology infrastructure for underwater sound. Not least of these contributions has been in the area of international standards. NPL's contributions include hosting the meeting of ISO TC43 SC3 – Underwater Acoustics in June 2016, the meeting being attended by 38 delegates from 10 countries. In the absence of the Chair of ISO TC43 SC3 through illness, the role of Acting-Chairman of the committee was provided by NPL for the week's meetings. The work of this standards committee has resulted in the recent publication of two new international standards for underwater acoustics: ISO 18405: 2017 – Underwater Acoustics – Terminology; and ISO 18406: 2017 - Measurement of radiated underwater sound from percussive pile driving. NPL led the work to produce ISO 18406, chairing the working group and leading the drafting. In addition to the above standards, NPL has also made contributions to the work on standards for ship noise measurement in deep water (ISO 17208-1:2016), and continues to contribute to the standards under current development. NPL also plays a significant role in the work of IEC TC87 where NPL chairs WG15, and where NPL has contributed to the revision of the recently published standard IEC 60500:2017 - Properties of hydrophones in the frequency range 1 Hz to 500 kHz (work led by China). NPL is also contributing significantly to the work to revise IEC 60565, and to the revision of IEC 600-50-801-32.

NPL continues to contribute to the development of guidance and good practice for the measurement and analysis of ocean environmental noise. As part of this, NPL serves on a number of expert international committees, including the EU Technical Group on (Underwater) Noise, and the International Quiet Oceans Experiment Standards (IQOE) Standards and Calibration Sub-committee. The IQOE is supported by the Scientific Committee on Oceanic

Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO), and aims to develop and promote better understanding of the levels of man-made noise in the global oceans.

Recent technical work involves an innovative approach to statistical analysis of underwater noise time series data, developed through the collaboration of the NPL staff of Underwater Acoustics and Data Science groups. The method is being used to analyse continuous underwater noise recordings collected around Diego Garcia Island and Cape Leeuwin, recorded by the monitoring stations of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). The data sets span over a duration of more than a decade. The analysis identifies changes in ocean sound levels as well as frequency content and quantifies, for the first time, the precision of such estimates making it possible to determine the long-term trends in deep ocean noise, a key parameter in the study of the long term impact of human activity on marine life. The use of the CTBTO data is part of an extended NPL collaboration with the organisation, which in the past has also included guidance on calibration and traceability, and investigation of long-term drift in hydrophone response. Figure 1 shows the results of some of the analysis undertaken.



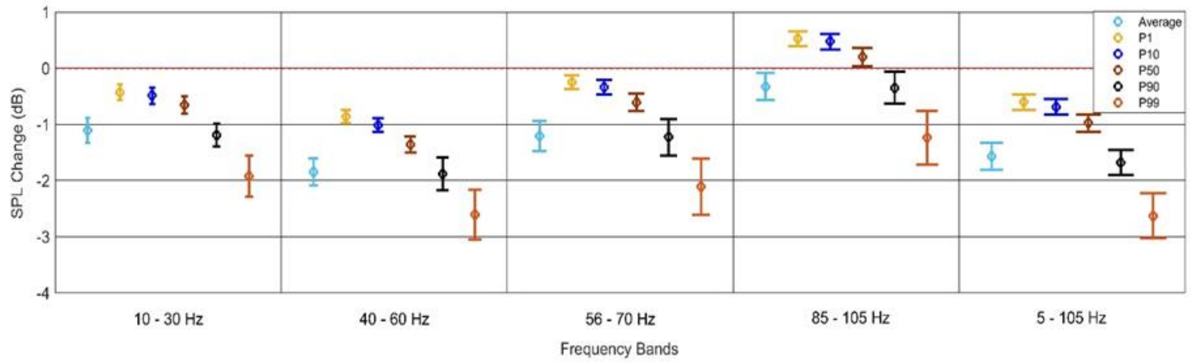


Fig. 1 Measured time series (upper) and estimation of trends in the mean and 5 different percentiles in ocean ambient noise and quantification of the estimates' uncertainties through application of regression with bootstrap resampling of the residuals (lower).

In related work, NPL has considered the design of an underwater sensing network, which were investigated using a simulated scenario based on the measurement of sound from ships in a shipping lane. Using models for the sources of the sound and for sound propagation, a noise map was calculated and measurements of the noise map by a sensor network within the region of interest were simulated. A compressive sensing algorithm, which exploits the sparsity of the representation of the noise map in terms of the sources, was used to estimate the locations and levels of the sources and thence the entire noise map within the region of interest. Although the spatial resolution to which the sound sources can be identified is generally limited, estimates of aggregated measures of the noise map can be obtained reliably obtained (work undertaken with NPL Data Science group and University of Oxford).

In other related work, NPL has applied its expertise to the development of measurement modelling techniques for the sound radiated by marine renewable energy developments in both the construction and operational phases. The last two years has seen NPL's work in this area published in the scientific literature. The NPL modelling using finite-element techniques of the sound radiation from marine pile-driving was compared to work of other researchers in a joint scientific paper. In addition, NPL's work to measure and characterise operational underwater noise radiated from a 3.6 MW monopile wind turbine has been published, as well as measurements of the operational underwater noise emitted by wave and tidal stream energy devices.

NPL is also a partner in the EU project "Underwater acoustic calibration standards for frequencies below 1 kHz (15RPT02 UNAC-LOW)" which aims to develop traceable calibration methods for devices used to monitor underwater noise. In addition to NPL, the partners include project coordinator TUBITAK (Turkey), DFM (Denmark), FOI (Sweden), and CNR-IDASC (Italy). The goal of the project is to develop the European metrological capacity in underwater acoustic calibration for acoustic frequencies from 20 Hz to 1 kHz by providing traceable measurement capabilities to meet the need for calibration of hydrophones and autonomous underwater acoustic noise recording systems. The project will develop the scientific and technical research capabilities in the field within Europe, and provide an improved metrology framework to underpin the absolute measurement of sound in the ocean. Many of the sound sources of most environmental concern emit most of their energy at low frequencies where traceability is currently relatively poor. The project outputs will provide the necessary traceability, support regulation and EU Directives (such as the Marine Strategy Framework Directive), and develop a coherent metrology strategy for Europe within this field (feeding into the metrology community via the EURAMET TC-AUV), significantly increasing the research capacity in the field. As a result of work carried out in the project, NPL has introduced a new traceable calibration service for autonomous recorders to provide improved underwater acoustic data. Figure 2 shows some example results for calibrations in the frequency range 20 Hz to 315 Hz. For free-field calibrations, the design of many autonomous recorders is such that the measuring hydrophone is mounted in close proximity to the recorder body and this can have a significant effect on the frequency and directional response of the system at kilohertz frequencies, and at frequencies below 1 kHz, resonances in the recorder body can influence the response.

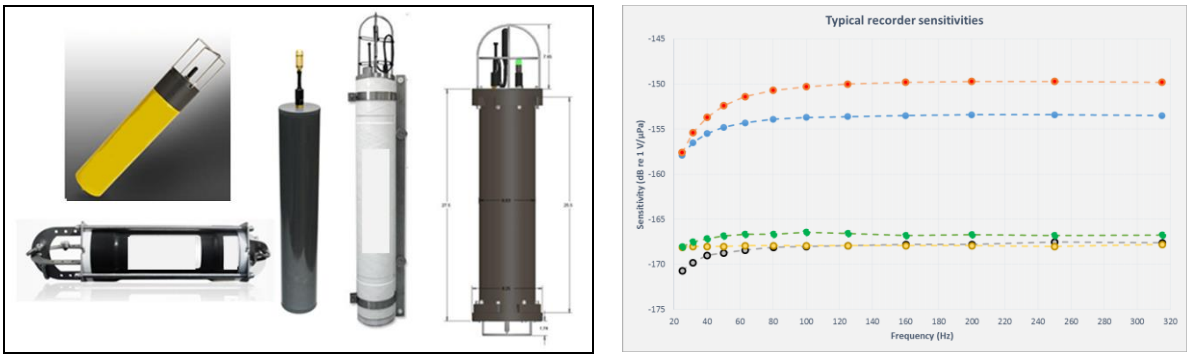


Fig.2 Images of typical marine autonomous acoustic recorders (left) and the results of calibration of such units in the frequency range 20 Hz to 315 Hz (left).

Further development in the testing of the acoustical properties of advanced materials at simulated ocean conditions continues, including the development and validation of test methods for characterising structured test objects by measurements undertaken in the acoustic near-field and using a pseudo-random sensor array. In the work, NPL is collaborating with the University of Exeter's EPSRC Centre for Doctoral Training in Metamaterials. Metamaterials are materials that have properties beyond those found in nature, and have found application across the electromagnetic and acoustic domains. NPL has recently made progress with the development of near-field scanning techniques for characterisation of complex test object and metamaterials. The work has utilised the automated scanning capability of the NPL open tank facilities. Materials are used in ocean acoustics as sonar window materials, transducer materials, and barrier materials, or stealth materials; and they are typically viscoelastic and require testing under controlled environmental conditions. In a collaborative research project with DSTL and University of Southampton, NPL established a rapid and accurate method for characterising their acoustic properties using the NPL Acoustic Pressure Vessel.

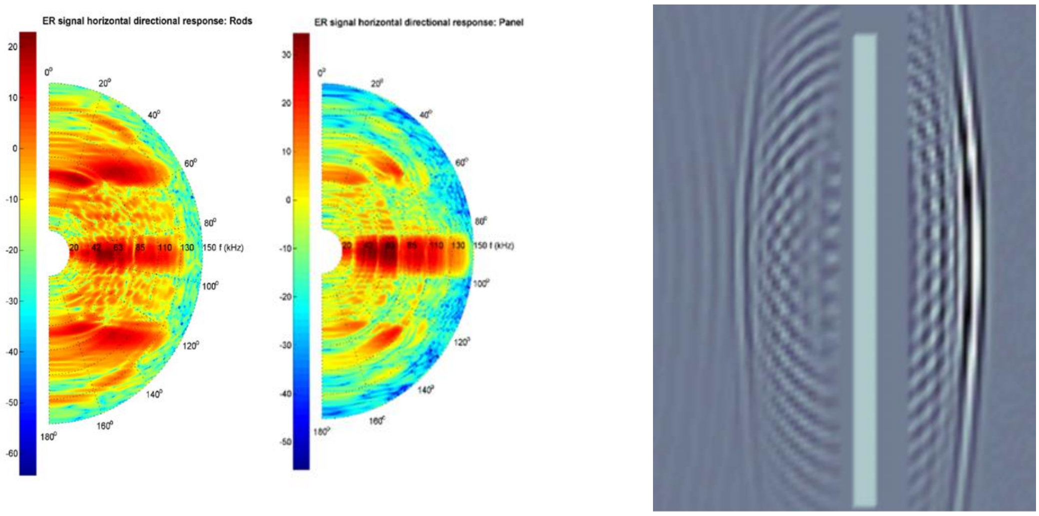


Fig 3. Echo Reduction polar frequency response for two test objects with periodic structure (left) with amplitude shown as colour map and frequency shown along the radius; On the right is shown an experimental nearfield scan of one of the test objects showing the transmitted and reflected waves, including the scattered waves generated by a diffraction grating effect of the periodic structure.

NPL continues to develop the next generation of NPL primary standards for underwater acoustics using optical techniques at frequencies from 100 kHz to 1 MHz. Recently, the interferometer performance has been compared directly with the ultrasonic primary standard interferometer over the frequency range 200 kHz to 3.5 MHz. Excellent agreement was obtained between these two independent realization of the acoustic pascal in water, with the results reported in a scientific paper.

NPL continues to provide knowledge transfer activities, contributing to meetings and fora organized within the UK and Europe. Examples include seminars organized by the UK Marine Science Coordination Committee and the Scottish Government, and the French L'institut interdisciplinaire de l'innovation in Paris. NPL has also run a number of training courses on good practice for underwater acoustic measurement and calibration for institutes from South Africa, Canada, and for UK Statutory Nature Conservation Bodies.

3 <u>Medical Ultrasound</u>

NPL has been involved a number of collaborative projects related to the safety and efficacy of diagnostic applications of therapeutic and diagnostic applications of ultrasound and a short summary of three of these will be presented.

Transvaginal ultrasound scans are carried out to support gynaecology, fertility and obstetric applications. This examination, particularly of the first trimester foetus, is a safety-critical imaging application because of the close proximity of sensitive tissues (foetus or ovaries) to the transducer that can produce heat during use. However, knowledge of how heat is generated and transferred to tissues remains limited. NPL has recently completed a project for the UK

Department of Health aiming at surveying and monitoring past and current practice of transvaginal scanning.

First of all, current clinical practice was monitored through a survey of more than 300 respondents including clinician and physicists. Moreover, more than 500 scans records, from the period 2009-2017, were analysed. The scan duration, mode employed and the acoustic parameters were extracted from the images. It was found that the average values for Thermal Index fell within the recommendations of the British Medical Ultrasound Society. Importantly, no significant statistical trend was observed in terms of scan duration, use of Doppler modes (which have higher output and greater potential ability to heat tissue) or the Thermal and Mechanical Indices over the period examined.

A sensorized phantom was designed, built and tested. It was composed of a block of tissue mimicking material with five fine wire thermocouples at specific and anatomically relevant positions. The phantom was used for an audit of 17 hospitals around the UK, 32 different combinations scanner/probe were tested, from 5 manufacturers. The output power was also measured using the NPL developed power meter. Results showed that the highest temperature increase is at the interface between the probe and the phantom, with transducer self-heating expected to be the major cause of this elevation. Deeper within in tissue, absorption plays a significant role in determining the overall observed temperature rise. All probes tested with a clinically relevant protocol, fell within the recommendations from National and International Committees, in terms of the generated temperature rise. However, activation of Doppler modes such as Colour Flow or Pulsed Wave can produce significant temperature increases. Furthermore, the Thermal Index indicated on the scanner display is significantly smaller than observed temperature rises in the phantom and the two figures were poorly correlated.

Finally, the temperature variations at the tip of a probe were measured for 24 scans carried out during *in-vivo* examinations. The results confirmed the findings of the previous analysis in terms of duration average, mode used and temperature elevation.

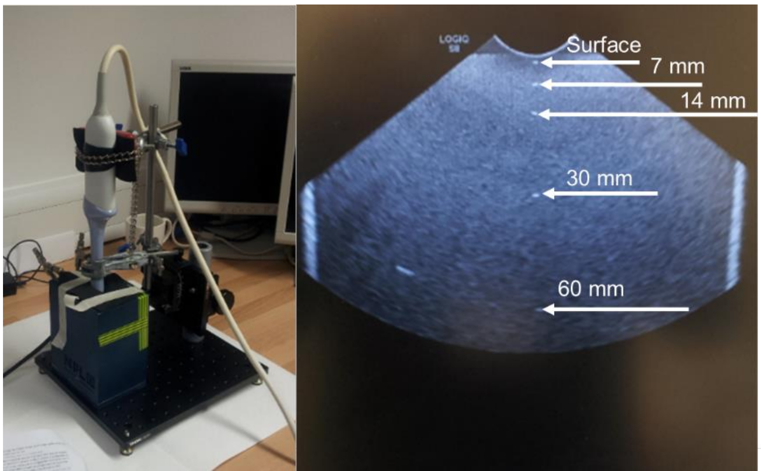


Fig 4. The phantom developed for the assessment of commercial probes (left) and an ultrasound image of the Tissue Mimicking Material block with the 5 fine wire thermocouples embedded at the indicated depths within the block.

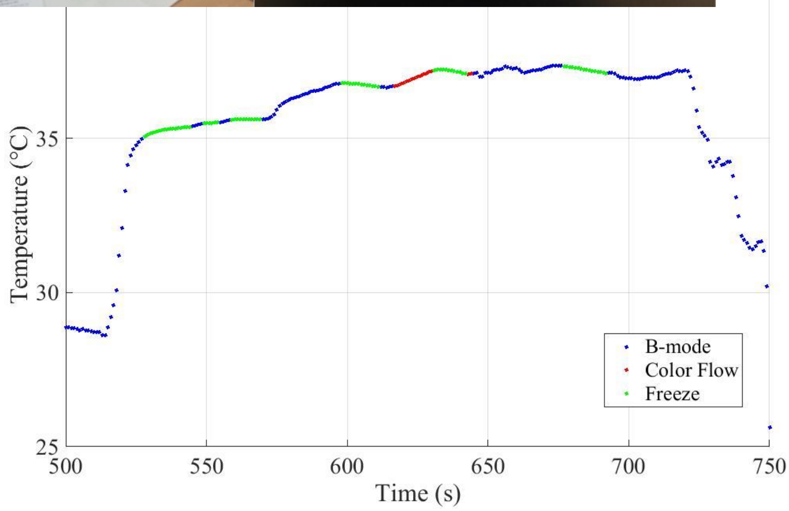


Fig 5. Example of a temperature curve at the surface of the probe during an *in-vivo* scan. Active modes obtained from the images are highlighted

A project whose objective was to design, manufacture and validate a demonstrator concept for a clinical breast imaging system based on phase-insensitive Ultrasonic Computed Tomography (piUCT) has been completed. The project was delivered by a consortium on NPL, Precision Acoustics Ltd, Designworks Ltd and University Hospitals Bristol. The system was built around, in terms of the detection technology, the phase-insensitive pyrolecetric detectors developed at NPL.

In terms of ensuring the success of any technology demonstration phase, there were three main performance criteria: the system needed to be fast enough to acquire data for a piUCT scan in an identified plane of the breast in less than 5 minutes; the signal-to-noise of the overall system was sufficient to allow scanning over useful depths of breast tissue 80 mm – 120 mm (this could mean needing to accurately measure signals whose amplitude differed by at least a factor of 1000). Finally, imaging resolution had to be sufficient to identify inclusions of a few mm in size. An image of a component part of the overall imaging system is shown in Figure 6 which displays a commercially available breast phantom purchased from the US manufacturer CIRS. These phantoms (multi-modality breast biopsy and sonographic trainers) were scanned at the site of the clinical partner in the project (University Hospitals Bristol) using both MRI and x-ray CT to establish the distribution of inclusions with the phantom. The phantom manufacturer (CIRS) also supplied samples of the base materials whose acoustic properties were determined at NPL to support a quantitative comparison with piUCT images.

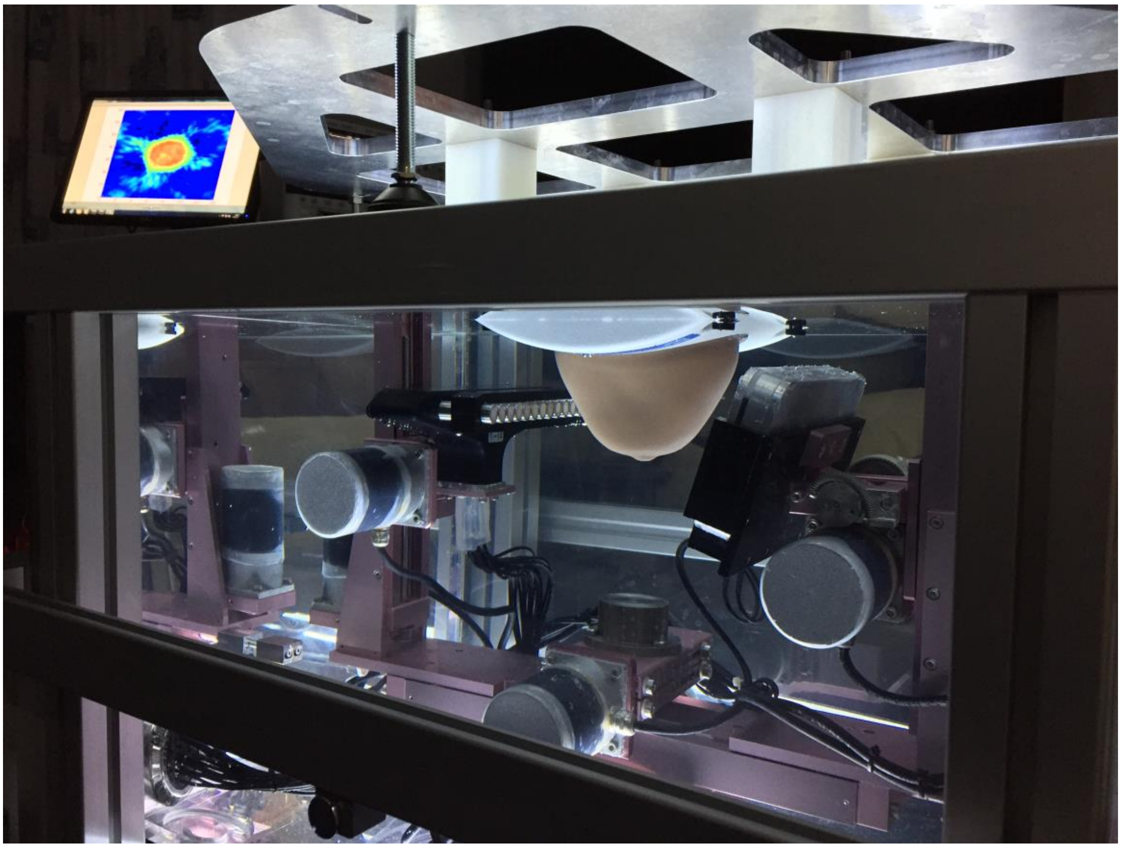


Fig 6. Image of the CIRS breast phantom deployed with the piUCT water-tank, between the angled large single element area sensor (right-hand side) and the linear transducer array (left-hand side).

In terms of the transducers that generated the ultrasonic radiation transmitted through the breast, a linear array of 14 tranducers each operating at 3.2 MHz is seen deployed as can be seemn in Figure 6.

Figure 7, below shows a comparison of initial UCT scans scans completed over a region of the phantom where we know (from the MRI images) there are likely to be no inclusions within the bulk, but where there are two different type of materials, including a thick outer, presumably protective, layer which the manufacturers call “z-skin”. It can be seen that piUCT is able the differentiate the two types of material in the phantom. The ring artefact is a characteristic of CT oberved over a number of modalities.

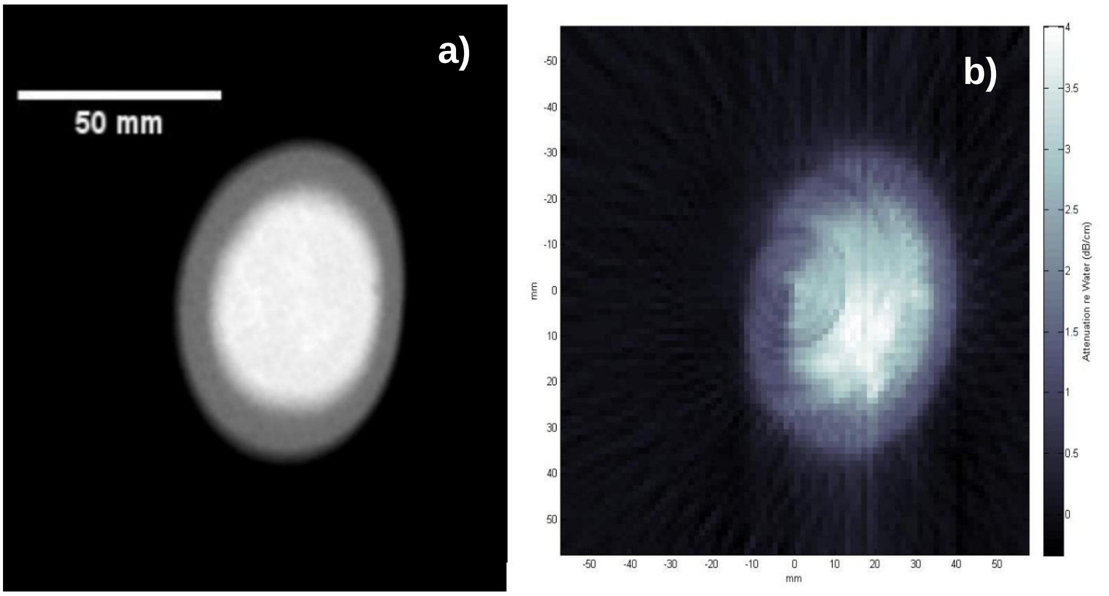


Fig 7. A comparison of two imaging modalities on a CIRS Model 043 breast phantom in the frontal plane at z = 17mm by: a) XCT and b) piUCT scans.

Research to assess, understand and optimise the performance of the system system continues. This involves the improvement of the achievable signal-to-noise and refining the imaging protocols (speeding up).

The last decade has seen a dramatic increase in the use of ultrasound as a surgical and therapeutic tool with many promising new applications emerging, some using very high power levels. Patients and doctors assume that ultrasound treatments are based on a good understanding of the required dose in tissue (in the same way as radiotherapy or phototherapy for instance) but in fact no such metrological infrastructure exists. Standardised and traceable dose quantities have yet to be developed for medical ultrasound therapeutic applications. This lack of a traceable dosimetry framework makes it impossible to determine dose-response curves and arrive at robust, personalised treatment plans. In May 2016, a Euramet-funded project, Dosimetry for Ultrasound Therapy (DUTy) was completed which was a collaboration between NPL, PTB, INRIM and TUBITAK and a number of other institutions.

The overall project aim was to begin the development of a metrological infrastructure to support ultrasound dosimetry bringing it in line with treatment planning applied for other longer established treatments, e.g. radiotherapy. Specifically, the project has developed i) definitions of the most important dose quantities within an overall framework relating exposure and dose to free-field quantities, ii) measurement methods appropriate for calibration and research laboratories and hospitals, and iii) new modelling capabilities to support treatment planning and risk assessment. The measurement infrastructure within European NMIs has been significantly broadened as a result of the project and scientific findings have been widely disseminated, including to the IEC where five new therapeutic ultrasound standards have been published or initiated.

In terms of the metrology, progress was made on a broad range of fronts. As well provide coordination for the project, NPL was engaged in the area of acoustic holography for characterization of therapeutic sources and fields. Although some HIFU treatments have progressed to clinical use, challenges remain for ensuring its safety and efficacy. A key component of these challenges is the lack of standard approaches for accurately characterizing the acoustic pressures generated by clinical ultrasound sources under operating conditions. An acoustic holography method was developed and successfully validated for characterizing 3D outputs of HIFU sources of various geometry including multi-element clinical arrays. This work was been carried out in collaboration between NPL, Moscow State University, University of Washington and Philips Healthcare.

Specific steps of the method are the following.

1. First, at a low output level, a calibrated hydrophone is used to measure in water the linear pressure magnitude and phase over a planar region in front of the source (see Figure 8). The position and orientation of such a region should be chosen so that it is crossed by most of the ultrasound field emitted by the source. A practical choice would be to position the measurement plane close to the source, with an orientation perpendicular to the ultrasound propagation direction and a size that extends beyond the geometrical cross section of the ultrasound beam. Such measurements represent a 2D hologram of the full 3D sound field.
2. Second, these measurements are used to holographically reconstruct the surface vibrations of the transducer and to set a boundary condition for a 3D acoustic propagation model.
3. Third, at a near-source location, the linear pressure magnitude is measured across a range of clinically relevant output levels, including the level used in holography measurements. The measurement location ideally should be near a local pressure maximum, while also being close to the source to minimize the possibility of nonlinear propagation effects. This single-point measurement allows relation of the source pressure level at various output settings to the source pressure level used for the hologram measurements.
4. Finally, nonlinear simulations of the acoustic field with a realistic boundary condition provided with the method are carried out over a range of source power levels. Simulation results can be validated for propagation in water by comparison with direct hydrophone measurements at the focus at both low and high power levels.

The acoustic holography approach utilizes linear field measurements to i) quantify the acoustic output level, ii) capture the pattern of vibrations at the transducer surface, and iii) define a realistic boundary condition of ultrasound source for a 3D nonlinear acoustic propagation model at any output settings of the source. In addition, the total acoustic power calculated from the measured hologram can be used to determine the source power at all measured output levels.

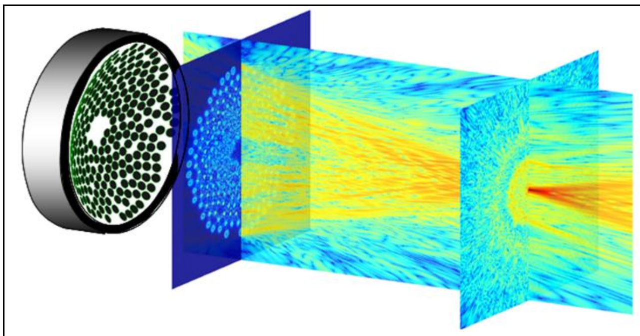


Fig 8. A diagram illustrating acoustic holography method to fully capture the vibrational pattern of the ultrasound source and the 3D field it generates based on a 2D pressure scan in a plane close to the transducer (shown towards the left side).

A number of cavitation meters on the market claim to characterise fields in ultrasonic cleaning baths: NPL completed an objective comparison of a selection of these devices. NPL's multi-frequency ultrasonic reference vessel provided the stable 21.06 kHz field as a test bed for sensor comparison. The results are summarised in the recent publication by Sarno et al. 2017.

Measurements from the devices were evaluated in relation to the known acoustic pressure distribution generated within the cavitation vessel as a means of identifying the sensor mode of operation and to examine the particular indicator of cavitation activity which they deliver. Through comparison of each device's performance in a stable, well characterised, cavitation reference vessel, at spatial locations where the acoustic pressure can be changed such that it is both above and below the inertial cavitation threshold, the study established that four of the six devices tested actually respond to the direct applied acoustic pressure, rather than the acoustic cavitation that arise from the pressure field. This approach has the potential to overestimate the level of cavitation in a vessel, with the implication of users believing that their cleaning baths are generating 'useful' cavitation over a wider region of fluid than they may do.

To provide more useful measurements of ultrasonic cleaning vessels for industry, cavitation meters should ideally deliver more specific indicators of cavitation other than acoustic pressure. Moreover, the ideal sensor must have a good spatial resolution of the field and possess a construction and design which minimally perturbs the acoustic field which they are measuring.

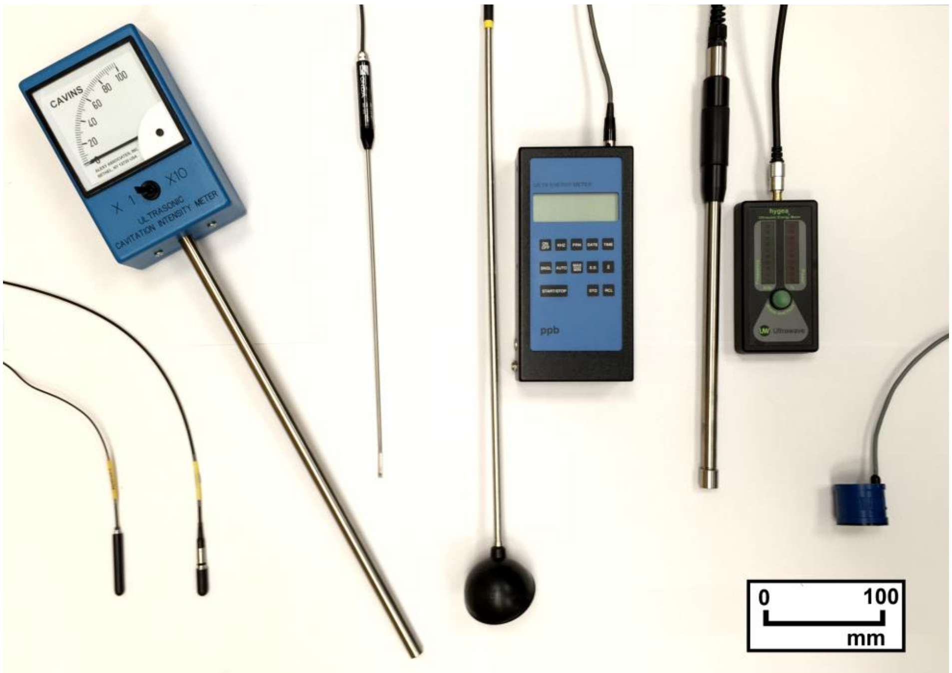


Fig 9. Photograph of the hydrophones and commercial cavitation meters used in this study. From left to right: TC4038, TC4013, CM-3-100, HCT-0310, pb502, Hygea Ultrasonic Activity Meter and CaviSensor™.

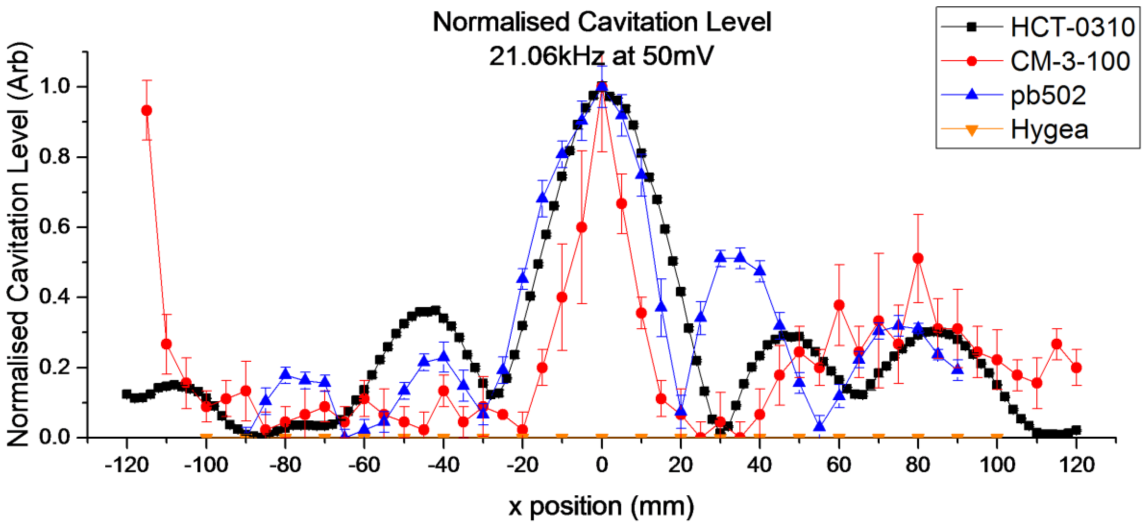


Fig 10. A comparison of normalised cavitation level as measured by the commercially-available cavitation meters at 50 mV drive. Plotted error bars are ±1 standard deviation. Note: the HCT-0310 error bars are too small to be visible on this plot.

4. Selected Publications, 2016-2017

4.1 Underwater Acoustics

Selected peer-reviewed publications:

Robinson S P, Lepper P A "Acoustics of marine renewables" in chapter "Applications of Underwater Acoustics", in *Applied Underwater Acoustics*, pp890, ISBN: 9780128112403, Elsevier, January 2017.

P M Harris, R Philip, S P Robinson and L Wang, "Monitoring anthropogenic ocean sound from shipping using an acoustic sensor network and a compressive sensing approach", *Sensors*, **16**, p415, 2016. [doi:10.3390/s16030415]

T. Koukoulas, S Robinson S Rajagopal and B Zeqiri, "A comparison between heterodyne and homodyne interferometry to realise the SI unit of acoustic pressure in water", *Metrologia,* **53** 891–898, 2016.

Lepper, P.A. and Robinson, S.P. "Measurement of Underwater Operational Noise Emitted by Wave and Tidal Stream Energy Devices", *Advances in Experimental Medicine and Biology* 11/2015; v. **875**: p. 615-622. DOI: 10.1007/978-1-4939-2981-8_74, 2016.

Hayman, G., Robinson, S.P. and Lepper, P.A. "The Calibration and Characterisation of Autonomous Recorders used in Measurement of Underwater Noise", *Advances in Experimental Medicine and Biology,* 11/2015; v. **875**: p. 441-445. DOI: 10.1007/978-1-4939-2981-8_52, 2016.

Lippert S, Nijhof M, Lippert T, Wilkes D, Gavrilov A, Heitmann K, Ruhnau M, von Estorff O, Schäfke A, Schäfer I, Ehrlich J, MacGillivray A, Park J, Seong W, Ainslie M, de Jong C, Wood M, Wang L, Theobald P. "COMPILE—A Generic Benchmark Case for Predictions of Marine Pile-Driving Noise", *IEEE Journal Of Oceanic Engineering*, **41**, (4), p1061-1071, 2016.

Pangerc, T, Theobald, P. D., Wang, L, Robinson, S.P., Lepper, P. "Measurement and characterisation of radiated underwater sound from a 3.6 MW monopile wind turbine", *J. Acoust. Soc. Am*. **140** (4), p2913-2922, October 2016.

Selected conference papers:

Foote, K. G., Robinson, S. P. and Theobald, P. D. "Quantitative imaging of acoustic backscatter from the seafloor", *Proceedings of the Institute of Acoustics*, **vol. 37** (pt. 1), p. 71-76, 2015.

Pangerc T, Robinson S P and Theobald P D. "Underwater Sound Measurement Data during Diamond Wire Cutting: First Description of Radiated Noise", *Proceedings of Meetings on Acoustics*, **27**, 040012 (2016); http://doi.org/10.1121/2.0000322, 2016.

Koukoulas, T; Piper, B; Robinson, S P. "Uncertainty contributions in the optical measurement of free-field propagating sound waves in air and water", *Proceedings of the International Congress on Sound and Vibration*, *ICSV23*, Athens, July 2016.

Robinson, S.P., Harris, P.M., Hayman, G., Ablitt, J. "Evaluation of uncertainty in the free-field calibration of hydrophones by the three-transducer spherical wave reciprocity method", *Proceedings of INTERNOISE2016*, p.7073-7082, Hamburg, August, 2016. ISBN Online 978-3-939296-11-9.

Robinson, S. P. "An international standard for the measurement of underwater sound radiated from marine pile-driving", *J. Acoust. Soc. Am.* **141**, pp3847, 2017;

Hayman G, Robinson S P, Pangerc T, Ablitt J, Theobald. "Calibration of marine autonomous acoustic recorders", *IEEE OCEANS 2017*, Aberdeen, May 2017.

Wang, L and Robinson, S. P. "A comparison of methods for measuring ship source level in shallow water", *Proceedings of the International Congress on Sound and Vibration*, *ICSV24*, London, July 2017.

Sotirakopoulos K, Harris P, Robinson S, Wang, L and Livina, V. "Identification and assessment of long term trends in underwater noise measurements", *Proceedings of the International Congress on Sound and Vibration*, *ICSV24*, London, July 2017.

4.2 Medical Ultrasound

Selected peer-reviewed publications:

Shaw, A, ter Haar G, Haller J and Wilkens V. "Towards a dosimetric framework for therapeutic ultrasound", International Journal of hyperthermia, 31(2), 182-192, 2015.

Hurrell A M and Rajagopal S. "The practicalities of obtaining and using hydrophone calibration data to derive pressure waveforms", IEEE Trans. Ultr. Ferro. Freq. Contr., 64(1), 126-140, 2017.

Gélat P N and Shaw A. "Relationship between acoustic power and acoustic radiation force on absorbing and reflecting targets for spherically focusing radiators,", Ultrasound in Medicine and Biology, 41(3), 832-844, 2015.

Fonseca M, Zeqiri B, Beard PC and Cox BT. "Characterisation of a phantom for multiwavelength quantitative acoustic imaging", Physics in Medicine and Biology, 61(13), 4950-4973, 2016.

Harfield C, Fury CF, Memoli G, Jones P, Ovenden N and Stride E. "Analysis of the uncertainty in microbubble characterisation", Ultrasound in Medicine and Biology, 42(6), 1412-1418, 2016.

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