Publishable Summary for 15RPT02 UNAC-LOW
Underwater Acoustic Calibration Standards for Frequencies Below 1 kHz

Overview

Ongoing concerns about the environmental impact of human activity, together with the emerging needs of industry and oceanographic science has increased the need for absolute measurements of sound in the ocean especially in the frequency range between 20 Hz and 1 kHz where anthropogenic sources of greatest environmental concern radiate most of their sound energy. To support the Marine Strategy Framework Directive (EU MSFD) and to underpin the absolute measurement of sound in the ocean a traceable metrology framework was required. This project developed new and extended existing calibration capabilities for hydrophones and autonomous underwater acoustic noise recording systems at acoustic frequencies below 1 kHz. After successful development of the calibration capabilities, all related partners participated in round-robin calibrations of commercially available hydrophones and underwater autonomous noise recorders to validate their calibration infrastructure. Outputs from the project have been used by partners to establish calibration services for hydrophones and autonomous noise recorders. Calibration has been performed for manufacturers, defence contractors, regulators, government institutes, and end users.

Need

With regards to marine environmental protection, the expansion of offshore activities has led to concern about the environmental impact of man-made sound upon marine fauna such as physiological effects (e.g. damage to hearing) or behavioural effects (e.g. flight response or displacement from habitats). An increase in background noise level may also have chronic effects (e.g. masking of biologically produced sound vital for communication and foraging).

The anthropogenic sources of greatest environmental concern radiate most of their sound energy in the frequency range between 20 Hz and 1 kHz. However, in this frequency range there has been a lack in the availability of traceable measurement standards, with much of the historic demand being for testing of active systems at kilohertz frequencies. There was both a direct and urgent need for traceable calibration of the hydrophone instrumentation used for measurements which was driven by regulation's increased demand for measurement. However, there is also a technology push provided by the development and increasing commercial availability of new instrumentation, specifically autonomous recorders that combine hydrophones and acquisition and data storage capabilities.

Currently, no specification standards exist describing the products for calibration of these instruments, and until this project there were no traceable calibrations made available by the metrology community. As a result, there was an urgent need to develop traceable measurement capabilities for the calibration of hydrophones and autonomous underwater acoustic noise recording systems at frequencies between 20 Hz and 1 kHz, including the 63 Hz and 125 Hz third-octave bands required by the EU MSFD and the development of new traceable calibration methods for autonomous noise recorders for which there are no established calibration methods. Underwater acoustics is a relatively immature field for metrology, and in addition to establishing a European calibration capability, a strategy must be developed for the long-term operation of the developed capabilities, contributing to a coherent metrology strategy for Europe within this field. This would provide a significant improvement in the use of available resources to better meet metrological needs and assure the traceability of national standards, and to develop a research capability within the metrology community.

Objectives

The overall objective of this project was to develop an absolute measurement technique for calibrating autonomous noise recorders at frequencies between 20 Hz and 1 kHz and disseminating these calibration capabilities in order to fulfil the related directive which is stated in the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC).

The project addresses the following scientific and technical objectives:

1. To develop traceable measurement capabilities to meet the need for calibration of hydrophones used for one off measurements at frequencies between 20 Hz and 1 kHz, and covering the 63 Hz and 125 Hz third-octave bands, as required by the guidelines for monitoring undersea noise within the EU MSFD.
2. To develop traceable measurement capabilities to meet the need for calibration of autonomous noise recorders and systems used for long-term ocean acoustic monitoring (periodically over the course of a year) at frequencies between 20 Hz and 1 kHz, including the 63 Hz and 125 Hz third-octave bands and to establish a research capability in this field.
3. To develop an individual strategy for each partner for long-term operation of the developed measurement capabilities including regulatory support, research collaborations, quality schemes and accreditation, contributing to development of a coherent metrology strategy for Europe within this field (discussed and agreed within the EURAMET community via the EURAMET TC-AUV), and significantly increasing the research capacity in the field.

Progress beyond the state of the art

Prior to the start of the project there were no traceable measurement capabilities for the calibration of hydrophones and autonomous underwater acoustic noise recording systems at frequencies between 20 Hz and 1 kHz, including the 63 Hz and 125 Hz third-octave bands required by the EU MSFD. There were also no established calibration methods for autonomous noise recorders.

The project developed and validated appropriate measurement methods for the calibration of hydrophones in the frequency range from 20 Hz to 1 kHz. As a conclusion of the project, two of the hydrophone calibration methods were selected from those described in the scientific literature or the related international standards have been implemented into new calibration systems. These were validated by comparison measurements between the project partners. Through this work, traceability for absolute measurement of sound in the ocean using hydrophones can now be provided across the EU countries, with partners now offering calibration services from their established facilities to their neighbouring countries.

The calibration methods developed in this project provide the ability to determine the key acoustic performance characteristics of the recorders, including the hydrophone and system sensitivities. The newly established methods to calibrate autonomous noise recorders have been implemented by the partners and services offered to stakeholders in neighbouring countries such as marine technology specialists and underwater acoustic manufacturers, with recommendations given to technical standards committees including ISO TC43 SC3 (Underwater acoustics) and IEC TC87 (Ultrasonics) for preparation of related standards. This is facilitated by members of the consortium who are active in the standards committees (the consortium contains the Convenor of several key Working Groups). The manufacturers and end users of noise-monitoring systems are being informed of the developments so that the improvements can be incorporated into their own work.

Establishing traceable calibration facilities for hydrophones and noise recorders by the partners sufficiently extended the capability of each related stakeholder. Also, these calibration facilities are used for providing calibration services by NMIs/DIs and guides for end users working in the field on underwater acoustic measurement and monitoring including the design and production of corresponding systems.

Results

Calibration of hydrophones

As a result of this project, the improved traceability for hydrophone calibration between frequencies of 20 Hz and 1 kHz provides manufacturers and users with vital confidence in the measurement result. IEC 60565:2006 was reviewed to select which methods for low frequency (20 Hz to 1 kHz) hydrophone calibration were used. Comparison calibration in coupling chamber and standing wave tube methods were selected for further

investigation.

TÜBİTAK developed new pressure coupling chambers and procedures for comparing the calibration of hydrophone sensitivity at frequencies from 20 Hz up to 2 kHz with better than 1 dB uncertainty. NPL developed three methods and associated procedures. The first method is for the calibration of hydrophones in the frequency range from 1 kHz to 250 Hz with uncertainty of between 0.5 dB and 1.0 dB with full uncertainty budget and validated methodology. The second method is for by comparison with other calibration techniques. the absolute calibration of hydrophones using a laser pistonphone in the frequency range from 20 Hz up to 160 Hz with 0.5 dB uncertainty. The third, and final method is for calibration of hydrophones in the frequency range from 25 Hz to 400 Hz with 0.5 dB uncertainty which compares to a calibrated microphone in a closed chamber and is traceable to acoustical standards. DFM developed a calibration method for hydrophones in the frequency range from 5 Hz up to 1600 Hz with uncertainty of between 0.3 to 1.0 dB depending on frequency using a coupling chamber for comparison with a reference set of microphones. FOI developed a calibration method for hydrophones by using Standing Wave Tube Method in the frequency band from 400 Hz up to 1 kHz with uncertainty of 0.8 dB.

In order to verify the developed methods and procedures, two different hydrophones, B&K 8104 and B&K 8106, were circulated between the partners for calibrations at one third octave band centre frequencies. TÜBİTAK calibrated both hydrophones in a pressure coupling chamber at frequencies from 20 Hz up to 2 kHz. NPL calibrated the B&K 8104 hydrophone at frequencies from 5 Hz to 400 Hz in a pressure chamber, and the B&K 8106 hydrophone at frequencies between 5 Hz and 400 Hz using pressure chamber methods and from 250 Hz to 2 kHz by extending the primary hydrophone calibration using free-field reciprocity adapted with signal modelling techniques. DFM calibrated both hydrophones in a pressure chamber at frequencies from 20 Hz to 2 kHz for the B&K 8104 hydrophone, and 5 Hz to 1.6 kHz for the B&K 8106 hydrophone. FOI calibrated both hydrophones at frequencies between 400 Hz to 1 kHz using a standing wave calibrator unit.

All calibration data measured by pressure coupling chambers are in a good agreement between partners at related frequencies (within their combined uncertainties). Also, the calibration result of NPL, for B&K 8106 hydrophone at frequencies from 250 Hz to 2 kHz by the extension of free field reciprocity method, is in a good agreement with comparison calibrations by pressure chamber methods at TÜBİTAK and DFM. According to the comparison calibrations results, the methods developed on pressure coupling chamber can calibrate hydrophones at frequencies from few Hz up to 1-2 kHz with uncertainties less than the targeted 1dB. The results that are obtained by the standing wave calibrator unit showed good agreement from 400 Hz to 1 kHz compared with those from the pressure chambers.

Calibration of autonomous underwater acoustic noise recording systems.

As a result of this project, pressure calibration methods for autonomous noise recorders have been established by NPL and TÜBİTAK for the frequency range between 20 Hz and 1 kHz with an uncertainty of better than between 0.5 and 1.5 dB depending on frequency. The methods developed by both partners calibrate using comparison to microphones in a closed air-filled chamber, a similar method to that established for pressure calibration of hydrophones. Successful calibrations have been carried out at NPL in the frequency range from 20 Hz to 315 Hz with uncertainties of 0.5 dB, and by TÜBİTAK in the frequency range from 20 Hz to 1 kHz with uncertainties of 1.0 dB or better. The results from NPL have shown that the methods may be extended down to 5 Hz in principle. Uncertainty budgets have been derived for the calibrations, and the results have been expressed as sensitivity levels in dB re 1 V/µPa and as linear calibration scale factors. A comparison between the results of NPL and TÜBİTAK was undertaken, with agreement of better than 0.5 dB over the common frequencies of calibration.

Free-field calibrations have been undertaken by FOI, CNR and NPL to investigate the effect on the response of resonances and scattering in some designs of recorder bodies, and results showed significant fluctuation in sensitivity at frequencies around a few kilohertz due to interference by scattered sound from the recorder body. NPL and FOI have also observed fluctuations due to body resonances at frequencies below 1 kHz. These results suggest that it would be a good recommendation to use an extension cable to move the hydrophone sensor away from the recorder body.

In addition, a field report has been prepared describing guidelines for the preparation, deployment and retrieval of autonomous noise sound recorders in natural test sites for long-term ocean acoustic monitoring for frequencies. The work, undertaken by FOI, CNR, and ISPRA in open water sites, used the SM4M recorder obtained by NPL for the project. Two round-robin calibration campaigns were performed in with different frequency ranges selected in the two sites, but with a common range from 200 Hz to 5 kHz. Uncertainties were

evaluated and found to be within ±1.7 dB except for frequencies lower than 200 Hz, in which the reduced output from the sound projector caused unfavourable signal/noise ratio. Differences between calibration results in the two sites were generally less than 2 dB, good agreement considering the frequency response of the device is not flat. Guidelines were provided for the operations of autonomous recorders in open water sites, with special attention to device preparation, mooring, deployment and recovery.

Individual strategy for long-term operation of the developed measurement capabilities

TÜBİTAK has gained new services for the calibration of hydrophones and noise recorders in the frequency range from 20 Hz to 1 kHz. TÜBİTAK will extend its CMC capability for pressure coupling chamber calibration in the frequency band 20 Hz to 1 kHz and increase the scope of its accreditation to ISO 17025.

NPL launched a new measurement service for autonomous recorders in 2017. Initially, this provides only pressure calibrations at frequencies from 25 Hz to 315 Hz by use of comparison in a closed chamber. NPL will extend its CMC capability for free-field calibration down to 250 Hz and increase the scope of its accreditation to ISO 17025.

At CNR, the existing free-field hydrophone calibration capabilities covering the 5 kHz – 300 kHz range have been integrated with new low-frequency capabilities using the Lake Nemi open-water site. The setup developed in the project for Lake Nemi allows free-field calibration of hydrophones and autonomous recorders extending the low frequency limit down to 200 Hz. An upgrade of instrumentation has been planned which will further extend the low limit down to about 100 Hz. The suitability of another open-water site has also been verified (Lake Bracciano, about five times deeper than Lake Nemi) in which the calibration setup will be used to reach a low frequency limit of at least 50 Hz, if not even lower. Both open-water sites are available all-year round.

At FOI, besides the laboratory calibration capacity from 5 kHz up to 300 kHz, there is a new capacity to calibrate both cabled hydrophones (reciprocity method) and acoustic recorders (comparison method) during a limited time of the year (January to April). Recent progress with new instruments extends the lower limit to 50 Hz and it is highly probable that the limit will be lowered even further. Intercomparison calibrations will have to be organized for validation of methods. In addition, there is a new capacity to calibrate both cabled hydrophones (reciprocity method) and acoustic recorders (comparison method) during a limited time of the year (January to April). Recent progress with new instruments extends the lower limit to 50 Hz and it is highly probable that the limit will be lowered even further.

Impact

The results of this project have been disseminated to end-users in industry, calibration laboratories, academia and the metrology community via training course, workshops, and publications at trade journals, well known peer-reviewed journals and conferences. Examples are given below:

- 8 presentations and posters at international and national conferences including the IEEE Oceans, European Underwater Acoustic Conference UACE2017, IMEKO TC19 Workshop on Metrology for the Sea and the International Metrology Congress CIM-2017. This also included the participation at the 2019 Underwater Acoustics Conference and Exhibition, a presentation at the UK Underwater Sound Forum (run by the UK Marine Science Coordination Committee) in November 2017 to a receptive audience of about 50 people (targeted at the UK community including regulators, users, manufacturers and research institutes) and the 61st Marine Measurement Forum.
- Exhibitions at the UK Ocean Business hosted at the UK National Oceanography Centre (NOC) in Southampton in both April 2017 and April 2019. NPL also attended the Undersea Defence Technology (UDT) exhibition in Glasgow during which meetings were held with a major UK manufacturer of marine acoustic recorders.
- 2 open access publications in peer-reviewed journals Measurement Science Technology and ACTA IMEKO. TÜBİTAK submitted a paper in a peer-reviewed journal on the design of pressure coupling chamber and results of hydrophone calibrations at frequencies from 20 Hz up to 2 kHz. Partners have also prepared two publications for imminent submission to peer-reviewed journals.
- A patent has been applied for through Turkish Patent and Trademark Office in April 2019 by TÜBİTAK for a new design of Coupling Chamber for the calibration of hydrophones at low frequencies. The priority date was taken with reference number TR2019/06367.

- Significant contributions have been made to the extensive revision of calibration standards produced by IEC TC87, including parts 1 and 2 of IEC 60565 which will be published by early 2020. A New Work Item Proposal for development of standards for calibration of marine acoustic recorders and digital hydrophones has been drafted and will be ratified at the next TC 87 meeting in China in October 2019. Contributions have previously also been made to three ISO TC43 SC3 standards on measurement of ocean noise (with regard to hydrophone and instrument calibration requirements). Partners NPL, DFM and TÜBİTAK have also disseminated the project outputs at EURAMET TC-AUV and CIPM CCAUV meetings.
- A total of 5 training courses by NPL and 2 training courses by TÜBİTAK have been held. The courses were targeted at different communities, such as regulators, manufacturers, metrology organisations, government institutes and civil services. The beneficiaries include: a marine environmental regulator in the UK, a Government metrology institute from South Africa, an oceanographic institute from Japan, a defence agency from Canada, and Turkish Naval Forces. A training workshop was also held for a mixed UK audience from industry on Ocean Acoustic Measurement.
- The project webpage (which has public access and a part restricted for partners) has been regularly updated with the latest progress.

A stakeholder workshop was held at CNR-INM in Rome in September 2018. The project stakeholder group has 23 contacts (exceeding the expectation from the plan which had a target of 15). The stakeholders include key contacts from manufacturers and suppliers, such as Wildlife Acoustics, RTSys, RSAqua, Ocean Instruments, Ocean Sonics, Teledyne-Reson. Also included are representatives of the user community such as Quiet Oceans, University of Catalunya, Institutfürtechnische und angewandtePhysik GmbH, Baker Consultants, CO.L.MAR, and Loughborough University. In addition, there are influential members of the regulatory authorities in both Europe (e.g. Marine Scotland) and the USA (e.g. NOAA). The group also includes metrology institutes (e.g. NIST, VNIIFTRI) and standards bodies (ISO TC43 SC3, IEC TC87 WG15). The stakeholder group reflects a truly worldwide interest in the project outputs, not just a European interest, with countries represented such as UK, France, Spain, Germany, Italy, USA, Canada and New Zealand.

Impact on industrial and other user communities

NPL launched a new measurement service for autonomous recorders in 2017 offering pressure calibration at frequencies from 25 Hz to 315 Hz by use of comparison in a closed chamber, covering the key frequency range needed to address traceability for the Marine Strategy Framework Directive. Before launch, NPL surveyed potential customers in the UK and adjacent EU states to obtain feedback on their calibration requirements. Since launch, a total of 55 recorder calibrations have been undertaken for UK and European customers including regulators, Government institutes, users and manufacturers. The new service has been the subject of a EURAMET Good News Story (EURAMET UNAC-LOW GNS). NPL have extended their calibration service for hydrophones down to 250 Hz in laboratory tanks (from 1 kHz). Calibrations have been undertaken for manufacturers, defense contractors, UK regulators, Government institutes, and end users. The technique has been used for calibrations of the CCAUV.W-K2 Key Comparison. At TÜBİTAK, new services for the calibration of hydrophones and noise recorders in the frequency range from 20 Hz to 1 kHz are included to the Industrial Service Catalogue of TÜBİTAK. Services have been made available to all users and manufacturers both inside and outside Turkey.

The calibration capabilities established in the project have already been used to support noise monitoring requirements of the marine acoustic community. Work from the project has been underpinning the work of an EU INTERREG project that started in January 2018 called JOMOPANS. The JOMOPANS project aims to undertake ambient noise monitoring for the North Sea in response to the EU Marine Strategy Framework Directive (MSFD). Additionally, NPL and FOI have calibrated autonomous recorders and hydrophones deployed within the North Sea for the JOMOPANS measurement phase (lasting for the whole of 2019). NPL and FOI are in the JOMOPANS consortium, with FOI responsible for maximising project impact and communication. NPL has been responsible for preparing JOMOPANS standards and procedures (including for calibration and deployment) and has incorporated several outputs from the project directly into the JOMPANS procedures.

In addition, responding to a direct request, a TÜBİTAK calibrated recorder was used to monitor the noise levels of the piling activity during bridge construction in Dardanelle Strait for 5 days sessions. The frequency band of

noise monitoring was from 20 Hz up to 39 kHz. Results were analysed by TÜBİTAK and compared according to the Technical Guidance for Assessing the Effect of Anthropogenic Sound on Marine Mammal Hearing, NOAA Technical Memorandum NMFS-OPR-55 July 2016.

Impact on the metrology and scientific communities

Each partner has developed an individual strategy for the long-term operation of the research and measurement capacity developed within the project, and the provision of calibration services from their established facilities to the user community in their own country as well as neighbouring countries. In the case of the three NMI/DI partners (NPL, TUBITAK, and DFM), each partner will maintain the standards developed within the project as part of their programme to provide measurement standards within their country and will disseminate the standards via calibration services. As a result of the project, NPL will now extend its CMC capability for free-field calibration down to 250 Hz and increase the scope of its accreditation to ISO 17025. TÜBİTAK will extend its CMC capability for pressure coupler chamber calibration in the frequency band 20 Hz to 1 kHz and increase the scope of its accreditation to ISO 17025. The strategies include support for regulatory bodies, research collaborations, quality schemes and accreditation within their country and where possible across Europe. Although the external partners within the project (CNR, FOI, ISPRA) do not have the responsibility to maintain and provide measurement standards, nevertheless the partners have committed to maintaining (and in some cases extending) their capabilities and making them available as a service to third-parties (including providing support for other EU ocean noise monitoring projects). CNR has extended its free-field measurement capabilities below the current low-frequency limit of 5 kHz, by routinely using its open-water site at lower frequencies. The free field lake calibration service of FOI is available for both domestic and international customers including manufacturers and government organizations. The current lower limit is approximately 200 Hz and the aim is to reach below 100 Hz in the near future.

After participating in the CIPM Key Comparison for the calibration of hydrophone at frequencies below 1 kHz, TÜBİTAK will extend its CMC capability and increase the scope of its accreditation to ISO 17025. As a result of round robin test, new services have started to be provided for the calibration of hydrophones and noise recorders in the corresponding frequency band.

A European metrology strategy for underwater acoustic calibration and traceability was the subject of further discussion at the April 2019 EURAMET TC-AUV meeting, and at the Sub-Committee for Ultrasound and Underwater Acoustics (SC-U). The TC-AUV metrology road maps are currently being reviewed, and the project outputs are informing the road-maps and the overall strategy. The draft road map for underwater acoustics has been prepared and will circulated shortly before ratification by TC-AUV. In addition, future EURAMET and CCAUV comparisons are being scheduled to follow on from the current CCAUC.W-K2 comparison as part of the TC-AUV strategy to extend the benefit to other laboratories in Europe (NPL and TÜBİTAK are already participants in the CCAUV comparison, with NPL as coordinator). CNR has continued negotiations within Italy to eventually obtain DI status for the metrology field of underwater acoustics and is also participating in TC-AUV meetings as a guest.

Impact on relevant standards

Within IEC TC87 WG15, significant contributions have been made to the extensive revision of existing standards, including IEC 60500:2017 (Properties of hydrophones in the frequency range 1 Hz to 500 kHz). In particular, considerable effort has been devoted to the revision of IEC 60565:2006 parts 1 and 2 (both on the subject of hydrophone calibration). Part 1 of the standard has now been successfully balloted at the CDV stage, and part 2 has been successfully balloted as an FDIS. Both parts were led by NPL who also chaired the IEC TC87 working group. A New Work Item Proposal for development of standards for calibration of marine acoustic recorders and digital hydrophones has been drafted and will be discussed and ratified after the end of the project at the TC 87 meeting in China in October 2019. A joint working group (JWG) with ISO TC43 SC3 will carry out the work and the JWG will invite input from the partners for this entirely new standard. Contributions have previously also been made to three ISO TC43 SC3 standards on measurement of ocean noise, with material covering hydrophone and instrument calibration requirements for measurements of low frequency sound sources in the ocean. For ISO 18406 (measurement of marine pile driving), much of the interest is in acoustic frequencies below 1 kHz and the guidance on choice of instrumentation, its calibration and deployment benefited from the work undertaken in the project. Work to draft ISO 17208-3 is ongoing, but the overlap with the project work is similar to that of ISO 18406, with the measurement of ship noise covering

similarly low frequencies. For the terminology standard ISO 18405, minor contributions were made to the definition of terms relating to hydrophones (hydrophone sensitivity, sensitivity, self-noise, etc).

In the Standards and Calibration sub-committee the prestigious International Quiet Oceans Experiment (IQOE), partners have contributed to technical discussions. As part of this committee, a list of currently available standards in the field has been drafted, and a list of world-wide calibration facilities is being drawn up. As part of the activities, NPL attended a meeting in Washington DC on standardisation for ambient ocean noise monitoring where NPL presented current activities on low frequency calibration (including work from the project). NPL will attend a meeting in The Hague in July 2019 on standardisation for ambient ocean noise monitoring.

Longer-term economic, social and environmental impacts

With regards to the economic and environmental impact of the project, the outputs provide more reliable and effective calibration methods and more robust uncertainty estimation which facilitate greater uptake and increase usage of autonomous recording systems, and hydrophones. The improved calibration methods enable manufacturers of recorder systems to meet the requirements of the instrumentation required by EU Directives for marine environmental noise. In addition to this, the outcomes of the project feed directly, through several project partners being directly involved in these monitoring programmes, into the ocean noise monitoring projects (such as OSPAR for North Sea and HELCOM for Baltic Sea). The developments within this project is taken up directly within the planned monitoring projects within regional seas. TÜBİTAK provided a monitoring service with a calibrated autonomous noise recorder to monitor the marine environment during the bridge construction across Dardanelle Strait. NPL has opened a calibration service in their facility to calibrate autonomous noise recorders used by customers to monitor marine environment. Several world-leading manufacturers of hydrophones and autonomous noise recorders are based in the EU and benefit from the project's output which should strengthen the European industrial infrastructure for the development of new products and services. Similarly, industrial consultancies can make use the enhanced traceability provided by this project, improving their capability for acoustic measurement in the ocean, both within and outside the EU. Finally, the project has improved collaboration between European NMIs in the field of underwater acoustics and calibration capabilities.

List of publications

[1] A Biber, C Çorakçı, A Golick, S Robinson, G Hayman, J Ablitt. S Barrera-Figueroa, S Buogo, S Mauro, F Borsani, S Curcuruto, M Linné, P Sigray, P Davidsson, "Calibration standards for hydrophones and autonomous underwater noise recorders for frequencies below 1 kHz: current activities of EMPIR "UNAC-LOW" project" - *ACTA IMEKO, June 2018, Volume 7, Number 2, 32-38, 2018* - DOI: 10.21014/acta_imeko.v7i2.542

[2] S Robinson, G Hayman, P Harris and G Beamiss, "Signal-modelling methods applied to the free-field calibration of hydrophones and projectors in laboratory test tanks" - *Meas. Sci. Technol.*, 29, 085001, 2018 - DOI: 10.1088/1361-6501/aac752

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RMG: -		