IMEKO International Conference on
Metrology for The Sea
Naples, Italy, October 11-13, 2017

Underwater acoustic calibration standards for frequencies below 1 kHz: current status of EMPIR "UNAC-LOW" project

S. Buogo[1], S. Mauro[1], J.F. Borsani[2], S. Curcuruto[2], A. Biber[3], A.C. Çorakçi[3], A. Golick[3], S. Robinson[4], G. Hayman[4], S. Barrera-Figueroa[5], M. Linné[6], P. Sigray[6], P. Davidsson[6]

[1] *CNR-INSEAN, 00128 Roma, Italy, silvano.buogo@cnr.it*
[2] *ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, 00144 Roma, Italy*
[3] *TÜBİTAK-MAM, Underwater Acoustics Laboratory, Kocaeli, Turkey*
[4] *NPL, National Physical Laboratory, Teddington TW11 0LW, United Kingdom*
[5] *DFM, Dansk Fundamental Metrologi A/S, DK-2800 Kongens Lyngby, Denmark*
[6] *FOI, Totalförsvarets forksningsinstitut, 164 90 Stockholm, Sweden*

Abstract **– "UNAC-LOW" is an ongoing project under EURAMET's EMPIR programme whose aim is to develop the European metrological capacity in underwater acoustics for the calibration of hydrophones and autonomous noise recording systems for frequencies below 1 kHz. The project will provide an improved framework to underpin the absolute measurement of underwater sound in support of regulation and EU Directives for which traceability is currently lacking. Methods for the calibration of hydrophones and autonomous recording systems in the frequency range from 20 Hz to 1 kHz will be developed and validated by comparison measurements between the project partners. Long-term operation of the calibration capabilities will be ensured by each partner, to provide a coherent metrology strategy for Europe within this field. Current activities regarding the design and preparation of calibration setup are here described, in view of round-robin calibrations and validation scheduled for year 2018.**

I. INTRODUCTION

"UNAC-LOW" [1] is an ongoing project funded by EURAMET under the EMPIR programme [2]. The project started in May 2016 and will last 3 years, with 6 EU partners participating from 5 States that face all major European seas (see Fig. 1). The project is led by TÜBİTAK Marmara Research Center (MRC) of Turkey, whose Underwater Acoustics Laboratory of MRC-Materials Institute is assigned as a Designated Institute in the field of underwater acoustics for Turkey. Other partners are 2 National Metrology Institutes (NPL, DFM) and 3 external partners (CNR, ISPRA, FOI). The project consortium is supported by a number of collaborators ranging from metrology institutes and agencies to manufacturers and service providers.

Fig. 1. UNAC-LOW consortium and collaborators

The goal of the project is to develop the European metrological capacity in underwater acoustic calibration for acoustic frequencies below 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 will provide an improved metrology framework to underpin the absolute measurement of sound in the ocean in support of regulation and EU Directives such as the Marine Strategy Framework Directive (MSFD), for which traceability is currently lacking.

There is an increased need for absolute measurements of sound in the ocean driven by ongoing concerns about the environmental impact of human activity, together with the emerging needs of industry and oceanographic science. The anthropogenic sources of most environmental concern radiate most of their sound energy in the frequency range between 20 Hz and 1 kHz, and there is a direct and urgent need for traceable calibration of hydrophones in this frequency range. Moreover, given the technology push provided by the development and increasing commercial availability of autonomous recorders, which combine hydrophones and acquisition and data storage capabilities, there is also an urgent need to develop traceable measurement capabilities for calibration of these instruments, for which no standards have been developed yet.

II. PROJECT OBJECTIVES

This project addresses the following scientific and technical objectives:

1. To develop traceable measurement capabilities for calibration of both hydrophones and autonomous recorders, for frequencies between 20 Hz and 1 kHz covering the 63 Hz and 125 Hz third-octave bands as required by the EU MSFD guidelines;
2. To develop an individual strategy for each participant 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 and significantly increasing the research capacity in the field.

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

The calibration methods developed in this project will provide the ability to determine the key acoustic performance characteristics of the recorders, including the self-noise of the hydrophone and system, the hydrophone and system sensitivities. The newly established methods to calibrate autonomous noise recorders will be implemented by the project partners and services offered to stakeholders in neighboring countries, with recommendations given to technical standards committees including ISO TC43 SC3 and IEC TC87 for preparation of related standards.

Each partner will develop a strategy for the long-term operation of the calibration capability developed in the project. This will include establishing regulatory support and research collaborations, as well as appropriate quality schemes and accreditation.

Also, each partner will develop a strategy for offering calibration services from their established facilities, both to their own country, and to neighbouring countries. The individual strategies will form part of a coherent metrology strategy for Europe within this field, discussed and agreed within the EURAMET community of NMIs/DIs via the EURAMET TC-AUV.

III. PROJECT DESCRIPTION

The project lists four workpackages (WP1 to WP4), each split into Tasks and Activities. All experimental activities are included in two workpackages, WP1 and WP2, that proceed in parallel with a similar layout and timetable.

WP1 deals with calibration of hydrophones and is led by project coordinator TÜBİTAK. Participants are DFM, NPL and FOI.

WP2 deals with calibration of autonomous noise recorders and is led by NPL. Participants are TÜBİTAK, CNR, ISPRA, and FOI.

The other WPs include activities by all partners to ensure proper dissemination of results. As a further means for knowledge transfer, output of the project will be used to extend existing training courses already offered by some partners, and to create new courses in different European areas.

A. Tasks and Activities

Both WP1 and WP2 are made of three sequential tasks: one for the review and selection of existing devices and calibration methods, one for the design and preparation of calibration setup, and one for the execution of round-robin experiments and for validating their results. During the desing and preparation task, each group of partners in WP1 and WP2 is free to use their choice of devices, either already available or to be rented or purchased, to implement their methods and to establish a calibration setup. The autonomous noise recorders will be typical of the more commonly encountered designs and will be capable of different configurations, either with or without a hydrophone fixed to the recorder body. The developed setups will be then employed in subsequent round-robin tasks with only one device, provided by the task leader, to be circulated among the participants. From the results, uncertainty budgets will be prepared and the total uncertainty will be calculated, with 1 dB target uncertainty for hydrophones. Comparison tests will also be conducted between the calibration setups and results will be used to estimate the equivalence of national measurement standards for hydrophones within the low frequency range between 20 Hz and 1 kHz.

Throughout the overall 36 months duration, 6 meetings, hosted by each partner, and one Stakeholder Conference are planned, with the latter to be held in autumn 2018. Deliverables are output at the end of major tasks in form of documented calibration procedures, field reports and guidelines. A Documented strategy report will also be produced after project end in April 2019.

Table 1 summarizes WPs and Tasks with their start and end months.

Table 1. Summary of project timetable. H = hydrophones, AR = autonomous recorders.

WP.Task	Task description	Start	End
1.1 (H)	Review of methods for low frequency calibration	May 2016	Oct 2016
2.1 (AR)	Review of marine autonomous noise recorders	May 2016	Oct 2016
1.2 (H), 2.2 (AR)	Design and preparation of calibration setups	Sep 2016	Oct 2017
1.3 (H), 2.3 (AR)	Experiments and validation of the setups	Sep 2017	Apr 2019
3.1 3.2 3.4	Strategic development Knowledge transfer Uptake and exploitation	May 2016	Apr 2019
3.3	Training	Oct 2017	Apr 2019
4.1-3	Project management	May 2016	Apr 2019

IV. CURRENT PROJECT STATUS

The project is near half of its duration. The first two operative tasks dealing with review of existing calibration methods and of available autonomous recorders have been completed with no delay. The following tasks regarding the design and preparation of calibration setups have been nearly completed, with only some minor delay due to procurement of autonomous recorders, either to be purchased or rented according to each partner's choice. Details of the calibration setups will be discussed among partners in the next project meeting to be held in October 2017 at DFM.

In the following paragraphs, the current status is given for activities related to hydrophones (WP1) and autonomous recorders (WP2).

Regarding the calibration of hydrophones, two calibration methods, among those included in the existing standard [3], have been selected for the experiments: the comparison method in a coupling chamber and the standing wave tube method.

In addition, other complementary activities are under way at NPL to evaluate other methods for frequencies below 1 kHz. These additional methods include an extension of free-field calibration using signal modelling techniques [4], the absolute method by a laser pistonphone [5,6], and the vibrating column method [7]. These studies are mostly funded by other projects but their outcomes will be highly valuable also for the present project.

A. Calibration of hydrophones with a coupling chamber

The first method for hydrophone calibration is realised by inserting the device under test and a calibrated reference receiver into a closed chamber together with a sound source, therefore exposing both receivers to the same acoustic pressure. The reference may be either a microphone or a hydrophone, depending on whether the chamber is air-filled or water-filled. As the acoustic frequency is increased, the pressure field inside the chamber becomes nonuniform, the reference and the device unter test are subject to increasingly different pressure levels and the method is no longer accurate. This happens when the acoustic wavelength approaches the same order of magnitude of the chamber size. To extend this upper frequency limit, that for an air-filled chamber is of a few hundred hertz, water-filled chambers may be used that allow an upper frequency limit beyond 1 kHz, in agreement with project requirements. However, liquid-filled chambers require the acoustic compliances of all boundaries (chamber wall, hydrophone boot, cables) to be calculated as they cannot be neglected compared with that of water. Another difficulty arises from air bubbles that may easily remain trapped inside the chamber. For these reasons, an air-filled chamber has been designed and produced where the souce drives a small air cavity so that the acoustic pressure is the same for both the reference and the device under test. With this design, a standard microphone can be used as a reference and a miniature loudspeaker as a source (see Fig. 2 for details).

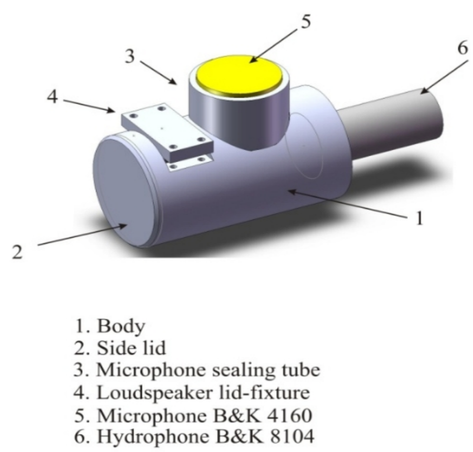

Fig. 2. Pre-design layout of the coupling chamber for calibration of hydrophones with the comparison method.

Initial tests on the designed chamber have been performed between 20 Hz and 1.2 kHz using a Bruel&Kjær 8104 as a hydrophone under test, a calibrated Bruel&Kjær 4160 microphone as a reference, and a micro-speaker type CDS-15118B-L100, used in cell phones and miniature headphones, as a sound source. The acoustic pressure of the source in air near its surface was estimated to be approximately 1 kPa for a typical radiated acoustic power of 0.1 W, under plane wave approximation. The first results confirmed a good SNR and essentially flat response below 1 kHz, with only some minor deviation below 50 Hz due to electrical loading of the measurement instrumentation. As an example of comparison with independent calibration data, calculations for 250 Hz yielded a sensitivity of -206.65 dB re 1V/µPa with estimated uncertainty of ±1 dB, in agreement with reference sensitivity of (-206.2 ± 0.7) dB obtained by free-field method at 1 kHz.

B. Calibration of hydrophones using a standing wave tube

The second method for hydrophone calibration is based on the standing wave tube method [3] and has been implemented by FOI using a USRD C100 calibration unit. This unit is made of a cylindrical cavity with an oscillating membrane mounted at the bottom for sound generation. The cavity is filled with water and the hydrophone is placed approximately at the tube center. As a device under test, a HTI-96 hydrophone was connected to a Wildlife Acoustics SM2M submersible recorder unit. Hydrophone voltage readout was done after completing the measurement session from its internal SD memory card, using a Matlab script to automatically detect signals for each frequency and their respective amplitudes.

With this setup, test calibrations for frequencies between 100 Hz and 1 kHz were done by comparison with a B&K 8104 reference hydrophone. Typical results are shown in Fig. 3: agreement with the factory calibration of the HTI-96 equal to -164.5 dB re 1V/µPa is confirmed for frequencies up to about 700 Hz. The reason for the large deviations observed for frequencies between 800 Hz and 1 kHz is currently under investigation.

C. Review of autonomous recorders

Activities regarding autonomous recorders have been initially focused on the review of their characteristics that are relevant for low frequency calibration.

While there are differences in the design of autonomous underwater acoustic recorders, their overall configuration is broadly consistent, with each device comprising a hydrophone, possibly with an integral preamplifier, connected to an electronics body containing an amplifier, analogue-to-digital converter (ADC), data storage media and batteries to power the unit.

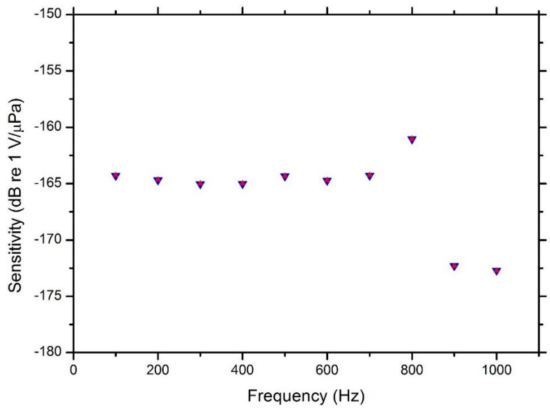

Fig. 3. Results of a test calibration of a HTI-96 hydrophone connected to a SM2M recorder using the standing wave tube method.

All recorders may be broadly categorised in two main configuration types, according to whether the hydrophone cable is hard wired to the recorder body, or attached to it via a detachable electrical connector. Each configuration type brings its own difficulties for low frequency calibration.

In the first configuration the recorder must be calibrated as one system while the hydrophone is attached to the device. This can pose particular calibration challenges for free-field calibration where sound waves interacting with the body may influence the measured sensitivity. If the hydrophone is not detachable from the body, a common feature with this configuration, low frequency pressure calibration may also be made logistically difficult because the entire body must be supported when inserting the hydrophone into a calibration chamber.

The second configuration type offers the possibility to calibrate the hydrophone separately from the recorder body. In some respects, this simplifies the calibration because the influence of the recorder body on the performance is minimised. However, in this case the separate calibrations of the hydrophone and recorder must be combined to form the overall system sensitivity. In doing this, the overall system sensitivity may not just be the simple product of the hydrophone and recorder sensitivities, and care must be taken to take into account any electrical loading effects.

For an autonomous recorder, the following characteristics need to be established in the frequency band of interest:

- System sensitivity
- System self-noise
- System dynamic range
- Directional response
- Frequency response

System sensitivity includes the preamplifier gain, which may take quite different values according to whether background noise or noise from a high-amplitude source is to be measured, in order to avoid signal degradation due to poor signal-to-noise ratio, clipping or nonlinearity.

The system self-noise is the electrical noise originating from the hydrophone and recording system. The equivalent sound pressure noise-floor of a recorder is the lowest sound pressure amplitude that can faithfully be represented with the device. To achieve acceptable signal-to-noise ratios, the system self-noise (expressed as the equivalent bandwidth noise pressure level) should be ideally at least 10 dB below this lowest signal level. It has been noted that not all the commercially available systems would be suitable for use in the measurement of very low level ambient noise in conditions near Sea State zero or Wenz minimum level (see Fig. 4).

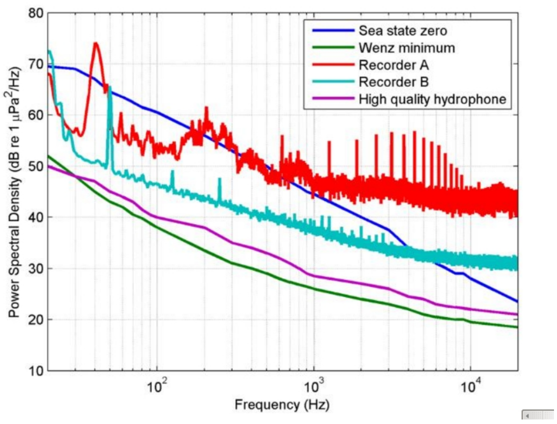

Fig. 4. Noise floor of three commercially available measurement systems compared with Sea State zero and Wenz minimum level (reprinted from [8]).

The measuring system response also needs to be linear over the full dynamic range, requiring that the system sensitivity be constant over the full range of measurable sound pressure. Systems with dynamic ranges in excess of 60 dB are preferred for measurement of high amplitude impulsive sources. As the dynamic range is related to the number of levels in the analogue-to-digital conversion, this implies that the system should feature at least a 10-bit ADC.

Autonomous recorders are normally required to possess an omnidirectional response. For a recorder with a hydrophone that is widely separated from the body, this is generally satisfied for frequencies up to 20 kHz. However, many of the commercially available devices consist of a hydrophone mounted either directly to the recorder body or close to it via a relatively short cable. The recorder body is typically an air-filled cylinder that can scatter the acoustic signal and cause perturbation of the response at kilohertz frequencies. It has been demonstrated that at kilohertz frequencies the recorder/hydrophone combination is not omnidirectional, and hence the sensitivity varies with angle of incidence, making the determination of the correct sensitivity challenging [9].

Although autonomous systems may be simply required to have a flat frequency response in the frequency range of interest to within an accepted tolerance (such as a 2 dB tolerance in ISO FDIS 18406), calibration of hydrophones and measuring systems would allow to correct for their variations in sensitivity with better accuracy.

If the recorded data are already processed into one-third octave bands before the correction for hydrophone sensitivity is applied, and the hydrophone sensitivity is not flat, care should be taken since a constant value across the band cannot be assumed.

A flat system sensitivity within the desired frequency range requires an adequate sampling rate of the ADC. A flat response also yields a uniform phase response which enables to faithfully represent the acoustic signal when peak-sound pressure or the waveform shape are to be measured.

The effect of the proximity of the recorder body may influence the system frequency response, due to a combination of the direct and reflected waves that causes interference. This problem is most acute for narrow-band signals received from a specific direction at kilohertz frequencies, and less severe for measurements of underwater sound in one third octave bands, where a degree of frequency averaging of the sensitivity will occur.

D. Calibration methodologies for autonomous recorders

For systems where the hydrophone can be detached from the recorder, the hydrophone may be calibrated independently using one of the methods described in previous sections. However, in this case the recorder system must also be calibrated by electrical signal injection and a separate procedure must be developed for this purpose. The two sensitivities must then be combined to provide the overall system sensitivity, that may not just be the simple product of the hydrophone and recorder sensitivities due to electrical loading effects. These latter are typical of certain types of recorder which are compatible with a range of different hydrophone models.

The method of low-frequency pressure calibration in an air-filled closed chamber has already been demonstrated to be applicable for autonomous recorders in the frequency range from 20 Hz to 315 Hz [8] and has been selected to be adopted in the project. This method has the disadvantage of only exposing the hydrophone to the acoustic field, so any effects from the body of the recorder will be unknown and need to be evaluated using free-field methods.

Free-field conditions ideally require a medium that is free of reflecting boundaries, which is very demanding to be realised in a laboratory tank below the kilohertz range [10]. The solution adopted by partners involved in this project is to use a larger volume of water for calibration such as a lake or reservoir so that a longer echo-free time is obtained for the measurements. At NPL, an open-water facility is available to support free-field recorder calibration. The facility is a fully instrumented floating laboratory situated on a freshwater reservoir with 20 m depth, allowing free-field measurement down to around 200 Hz. Similarly, FOI have a mobile measurement facility on the ice sheet that forms over the Hornavan Lake, Arjeplog, in Lapland, Sweden. The facility offers a maximum depth of 220 m and is covered by an ice cap of between 0.8 m and 1.0 m in March. The facility supports routine measurements down to 50 Hz. CNR-INSEAN owns a facility with exclusive access to the Nemi Lake near Rome, a natural lake with about 1.5 km mean diameter and 34 m depth. This site is routinely used for acoustic measurements on marine systems and offers a mild climate with little precipitation and wind for most time of the year, a background noise below Sea State zero, and absence of any other man-made activity. Finally, ISPRA can have access to Bracciano Lake, another natural lake 30 km north of Rome with about 8 km diameter and 150 m depth, that also exhibits moderate climate changes and minimal noise level. All these open-water sites will be used in round-robin experiments to be performed during year 2018.

In addition to the self-noise of the measuring system itself, data measured using free-field methods in open-water sites can also be contaminated by noise originating from the platform or method of deployment. The more common sources of platform and deployment noise that have been identified are: flow noise, cable strum (low frequency vibration due to currents), mechanical noise from debris and mooring cables, water surface heave and agitation. To minimise these noise components, proper guidelines and draft field reports are being produced for preparation, deployment and retrieval of autonomous recorders by the involved partners.

In addition, the diffuse field calibration method shall also be investigated. This method has been demonstrated in air by DFM for microphones [11] and recently in a laboratory water tank by VNIIFTRI (Russia) for a receiver attached to a towed body or recorder in one third-octave band levels [12, 13]. This approach accounts for the measured sound wave that is incident on the hydrophone as well as the measured sound that has been scattered off the recorder body. NPL will investigate diffuse field methods in the NPL facilities as part of the project.

V. REFERENCES

[1] Project web site: www.empir-unaclow.com

[2] The project has been accepted under EMPIR's Research Potential section in 2015 with project code 15RPT02.

[3] IEC60565:2006 Underwater acoustics – Hydrophones – Calibration in the frequency range 0,01Hz to 1MHz.

[4] Hayman, G., Robinson, S.P., Harris, P.M. and Beamiss, G.A. “Signal modelling techniques to extend the measurement frequency range downwards when echo-free time is limited”, UACE2015 - 3rd Underwater Acoustics Conference and Exhibition, Crete, June 2015.

[5] Barham, R.G and Goldsmith, M.J. “The application of the NPL laser pistonphone to the international comparison of measurement microphones”, *Metrologia* 44 (2007) 210–216.

[6] W. He, L. He, F. Zhang, Z. Rong and S. Jia. “A dedicated pistonphone for absolute calibration of infrasound sensors at very low frequencies”, *Meas. Sci. Technol*. 27 (2016) 025018.

[7] 5. Schloss, F., and Strassberg, M. Hydrophone calibration in a vibrating column of liquid. *J. Acoust. Soc. Am*. 34 (7), 1962, pp.958-960.

[8] 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; 875: 441-445, 2015.

[9] Hayman G., Robinson S. P. and Lepper P.L. “The calibration and characterisation of autonomous underwater recorders”, Proceedings of UA2014 - 2nd conference on Underwater Acoustics, Greece, 1125-1132, 2014.

[10] Bobber, R. J. *Underwater Electroacoustic Measurements,* Peninsula Press, New York, 1988.

[11] Barrera-Figueroa, S, Rasmussen K, and Jacobsen, F. “A note on determination of the diffuse-field sensitivity of microphones using the reciprocity technique”. *J. Acoust. Soc. Am*. 124 (3), 1505-1512, 2008.

[12] Isaev A. E. and Chernikov I.V. “Laboratory Calibration of an Underwater Sound Receiver in the Reverberation Field of a Noise Signal”, *Acoustical Physics*, 61 (6), 699–706, 2015.

[13] Isaev A. and Nikolaenko A. “The calibration of a receiver of the measurement of ambient underwater noise”, Proceedings of Internoise2016, Hamburg, Germany, 2016.