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Calibration standards for hydrophones and autonomous underwater recorders for frequencies below 1 kHz: current activities of "UNAC-LOW" project

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ABSTRACT
The project entitled "UNderwater Acoustic Calibration standards for frequencies beLOW 1 kHz" ("UNAC-LOW"), currently active within the European Metrology Programme for Innovation and Research (EMPIR), is presented by describing its objectives and current activities. The project aims at developing the metrological capacity of the European Union (EU) for the calibration of hydrophones and autonomous recording systems for the frequency range between 20 Hz and 1 kHz, for which traceability is presently not fully available. In this way, EU metrological capacities for absolute measurement of underwater sound will be improved, with a direct effect on the implementation of regulation and EU Directives that require underwater acoustic measurements to be traceable. After having completed the initial project tasks regarding the review of existing methods and the design of the experimental setups, comparison measurements between the project partners are currently under way and their results will be validated and presented upon project end after first quarter of 2019. To ensure long-term operation of the calibration capabilities by each partner, a coherent EU metrology strategy for underwater acoustics will be developed as one of the main project outcomes. Current activities include the implementation of the calibration setups developed in earlier stages of the project for both hydrophones and autonomous recorders. The methods that shall be used for hydrophones are the pressure method in a closed chamber and the standing wave tube method. For autonomous recorders, in addition to the above methods, calibrations will be performed using free-field methods in different open-water test sites possessing suitable characteristics for low frequency measurements.

Section: RESEARCH PAPER

Keywords: underwater acoustics; low-frequency hydrophone calibration; underwater noise recorders; EMPIR

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1. INTRODUCTION

"UNAC-LOW" [1] is a European metrology project aimed at developing low-frequency calibration standards in underwater acoustics together with a coherent European strategy for long-term operation of developed capacities. In this field, traceability is currently not readily available across Europe while only a limited number of institutions outside Europe offer low-frequency calibration services for hydrophones. The project started in May 2016 and will last three years until April 2019. The six participants (see Figure 1 and Table 1) are from 5 EU Member States, each with access to different European seas (see Figure 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 entities that have expressed interest in the project, including metrology institutes and agencies, manufacturers and service providers. The project is co-funded by the European Union's Horizon 2020 framework research programme and by the European Association of National Metrology Institutes (EURAMET) through the European Metrology Programme for Innovation and Research (EMPIR) [2].

The main project objective is to improve the European metrological capacity in underwater acoustic calibration for acoustic frequencies from 20 Hz to 1 kHz. To do so, traceable measurement capabilities will be developed to meet the need for calibration of hydrophones and autonomous recording systems, that are both used for measurement of underwater noise at sea. The project also aims at developing the scientific and technical research capabilities of the participating partners, providing an improved framework to underpin the demand for traceable measurement of sound in support of regulation and EU Directives such as the Marine Strategy Framework

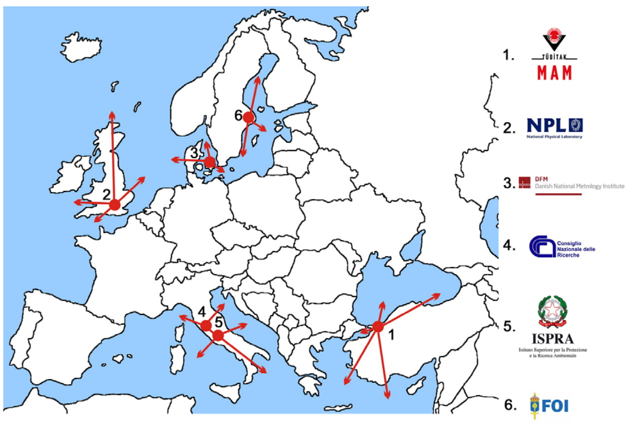


Figure 1. UNAC-LOW participants and their location within Europe.

Table 1. Details of UNAC-LOW participants. Participant status: NMI = National Metrology Institute, DI = Designated Institute, Ext = External funded partner.

Acronym	Full name	Country	Status
TUBITAK	*TÜBİTAK Marmara Research Center, Materials Institute, Underwater Acoustics Laboratory*	Turkey	DI
NPL	*National Physical Laboratory*	United Kingdom	NMI
DFM	*Dansk Fundamental Metrologi A/S*	Denmark	NMI
CNR	*National Research Council of Italy, Marine Technology Research Institute*	Italy	Ext
ISPRA	*National Institute for Environmental Protection and Research*	Italy	Ext
FOI	*Swedish Defence Research Agency*	Sweden	Ext

Directive (MSFD). In this field, traceability is currently lacking and the development of international standards for measurement of underwater ambient noise has been recently recommended in MSFD guidance reports issued by the EU Technical Subgroup on Noise [3].

The reliability and quality control of data is recently assuming key relevance for the long-term observation of marine parameters based on autonomous platforms, that often includes monitoring of underwater noise [4]. The need for absolute measurement of sound is therefore increasing as it is driven by concerns about the environmental impact of anthropogenic noise, so that not only oceanographic science but also industry is showing an increased interest in this field as regulatory compliance imposes more demanding requirements on monitoring instrumentation and methods. The frequency spectra of man-made noise sources of major concern are concentrated in the range between 20 Hz and 1 kHz, so a direct and urgent need for traceable calibration of hydrophones falls in this frequency range. International standards already exist [5], [6] that describe calibration methods for hydrophones below 1 kHz that may potentially be adopted in the present project. Among the institutions that currently offer calibration services world-wide in the frequency range of interest, only one is located within Europe (project partner NPL) providing calibration services for hydrophones below the kHz range that are traceable to primary standards for air acoustics. Among low-frequency calibration services available outside Europe, the primary calibration method with a coupler reciprocity chamber is routinely used in the USA and has recently been demonstrated for the complex (magnitude and phase) calibration of hydrophones between 1 Hz and 2 kHz [7].

Regarding autonomous recorders, which combine hydrophones and acquisition and data storage capabilities, given the technology push provided by their development and their increasing commercial availability, and since no standards have been developed yet for their calibration, there is also an urgent need to develop traceable measurement capabilities that account for this category of devices. Such capabilities are generally not simply based on the available calibration methods for hydrophones, since the latter are generally calibrated below the kHz range using pressure methods that require fitting them air-tight into a specific closed volume, which may not be readily feasible for all recording systems given the wide variety of acoustic sensors they can employ.

Section 2 will describe the project objectives, and in section 3 an overview will be given of its organization. In section 4 the current status of ongoing activities will be given. Finally, in the concluding section the project achievements obtained so far will be outlined.

2. PROJECT OBJECTIVES

The scientific and technical objectives of UNAC-LOW project are the following:

1. To develop traceable measurement capabilities for calibration of hydrophones and of 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;

3. To contribute to the development of a coherent metrology strategy for Europe within this field;
4. To significantly increase Europe's research capacity in this field.

In the project, appropriate measurement methods for the calibration of hydrophones in the frequency range from 20 Hz to 1 kHz will be developed and proficiency will be gained in the implementation of such methods. Upon project conclusion, the selected calibration methods will be implemented into new calibration systems that will be validated by comparison measurements between the project partners. Through this work, traceability for low-frequency underwater acoustic measurements will be provided across the EU countries, with project partners offering calibration services from their established facilities to the overall market, including other Countries within and outside the EU.

The key acoustic performance characteristics of the recorders will also be determined through the developed methods. Such characteristics include the self-noise of the hydrophone and system, and the hydrophone and system sensitivities. The project partners will each implement their newly established methods and services will begin to be offered to the stakeholder community. Moreover, recommendations will be sent to technical standards committees including ISO TC43 SC3 and IEC TC87 for preparation of related standards.

A long-term strategy for the operation of the calibration capability will be developed by each project partner. This will be done by establishing regulatory support and research collaborations, as well as adopting appropriate quality schemes and accreditation.

To offer calibration services both to their own country, and to neighbouring countries from their established facilities in a coherent way, each partner will develop an individual strategy that 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.

3. PROJECT DESCRIPTION

The experimental activities are arranged in two workpackages that proceed in parallel: workpackage 1 (WP1) deals with calibration of hydrophones and workpackage 2 (WP2) deals with calibration of autonomous recorders.

Both WP1 and WP2 are arranged in three sequential stages with corresponding 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 design 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 implemented methods are described in technical procedures and field reports, and will be included in final deliverables at the end of project. The autonomous recorders will be typical of the more common designs among the fairly large number of models (over 30, as reported in [8]) that are currently available on the market. The selected models 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.

The project schedule also includes 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.

4. CURRENT PROJECT STATUS

The project has completed its first stages dealing with review and design of calibration methods, and is proceeding along its final operative stage. The first parts 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 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 have been discussed among partners and are currently being implemented by participants.

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

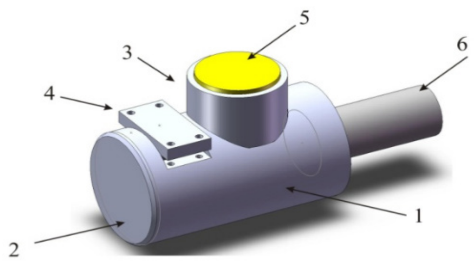
Two secondary calibration methods for hydrophones have been selected, among those included in the IEC existing standard [5]. Such methods, the comparison method in a coupling chamber and the standing wave tube method, will be used for the experiments. Regarding autonomous recorders, the above secondary methods will be adopted for pressure calibrations. In addition, for specific frequency ranges according to the characteristics of available open-water sites, free-field methods will be used: the three-transducer reciprocity primary method and the method of comparison with a reference hydrophone calibrated by pressure method.

To evaluate other methods for frequencies below 1 kHz, possibly also including primary calibration methods, NPL is also currently involved in activities that aim at an extension of free-field calibration using signal modelling techniques [9], the absolute method by a laser pistonphone [10], [11], and the vibrating column method [12]. These studies, although mostly funded by other projects, are obtaining useful results that shall be compared with those of the present project.

4.1. 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 non-uniform, the reference and the device under 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: for 1 kHz in air at standard conditions this length is about 30 cm. The upper frequency limit of the chamber can be extended in case when the chamber is filled by liquid in which the acoustic wavelength is a few times longer than in gas. Coupling chamber has been designed and produced where the source 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 Figure 2 for details).

Using an air-filled regime, 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 sound 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 signal-to-noise ratio and essentially flat response below 1 kHz, with only some minor deviation below 50 Hz due to electrical loading of the measurement instrumentation. Figure 3 shows the first results of a test calibration made with the designed chamber in the frequency range from 20 Hz to 1 kHz. 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.



1. Body
2. Side lid
3. Microphone sealing tube
4. Loudspeaker lid-fixture
5. Microphone B&K 4160
6. Hydrophone B&K 8104

Figure 2. Pre-design layout of the coupling chamber for low-frequency calibration of hydrophones with the comparison method. The chamber dimensions are 54 mm length by 23 mm internal diameter.

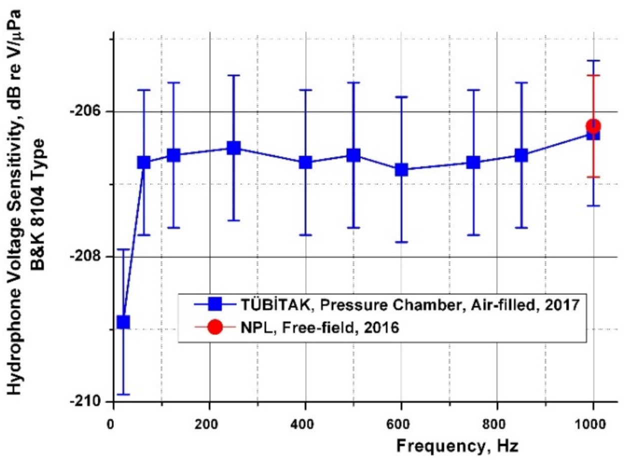


Figure 3. Preliminary results of pressure calibration of a B&K 8104 hydrophone using the coupling chamber shown in Fig.2, compared with reference calibration point at 1 kHz on the same device using free-field method.

4.2. Calibration of hydrophones using a standing wave tube

The second method for hydrophone calibration has been implemented by FOI using a calibration unit (model C100, Underwater Science, Research & Development, Inc., USA) which is based on the standing wave tube method [12]. This unit is made of a cylindrical cavity with an oscillating membrane mounted at the bottom for sound generation (see Figure 4). 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, early tests for frequencies between 100 Hz and 1 kHz were done by comparison with a B&K 8104 reference hydrophone. Typical results show general good agreement to within 1 dB with the factory calibration of the HTI-96 equal to -164.5 dB re 1V/μPa for frequencies from 100 Hz up to 700 Hz. Unexpectedly large deviations, from 3 dB up to 8 dB, have been observed for frequencies between 800 Hz and 1 kHz, whose cause is currently under investigation.

4.3. Review of autonomous recorders

The first activities that dealt with autonomous recorders were focused on the review of their characteristics that are relevant for low frequency calibration.

The overall configuration of autonomous underwater acoustic recorders is broadly consistent, while there are differences in their design. Each device is usually made of 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.

All recorders may be broadly categorised in two main categories according to their overall configuration: that is, 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

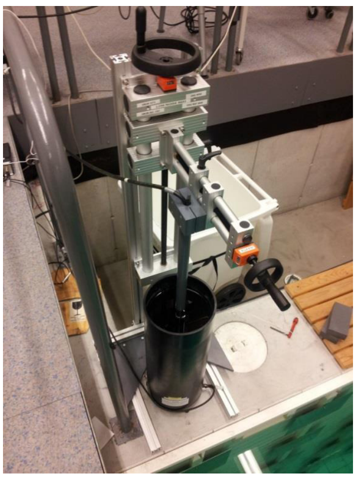


Figure 4. Overview of the setup for low frequency hydrophone calibration using the standing wave tube method.

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 electrical noise originating from the hydrophone and recording system is also defined as the system self-noise. 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 [13].

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 of the ADC, and accounting for a precision loss of 2 or 3 bits due to internal noise, this implies that the system should feature at least a 12-bit ADC.

For a recorder with a hydrophone that is widely separated from the body, the usual requirement of omnidirectional response is generally satisfied for frequencies up to 20 kHz. However, many of the commercially available devices, including the ones used in the project, consist of a hydrophone mounted either directly to the recorder body or close to it via a relatively short cable (see Figure 5). 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 [14]. For this category of devices, since the direction of arrival of incident sound is normally not known, a significant directional response would therefore be a disqualifying characteristic.

Figure 5. Detail of an autonomous recorder used for the calibrations, with the hydrophone and end cap removed from the main body showing the internal recording device. Body dimensions are approximately 16 cm diameter by 80 cm length.

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 that 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.

Figure 6 shows an example of early test calibrations performed on a number of various autonomous recorders by

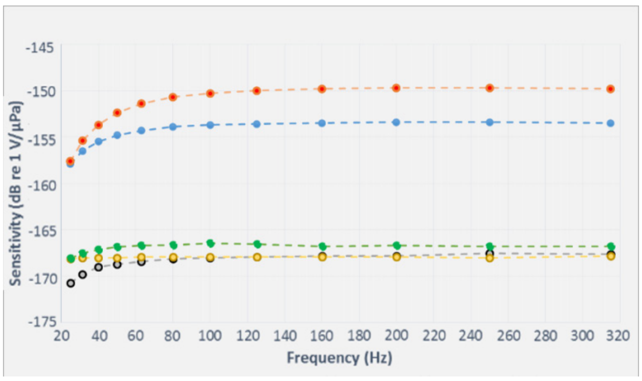


Figure 6. Typical examples of measured receiving sensitivities, in dB re 1 V/µPa as a function of frequency, of commercially available autonomous recorders. Each curve is for a different model.

inserting their hydrophones in a closed chamber, therefore excluding all effects coming from the recorder body. The data show some correlation between the sensitivity value in the flat portion for higher frequencies and the cutoff frequency, approximately between 50 and 100 Hz, below which a decay begins mainly due to electrical loading of the input stage of the preamplifier.

4.4. Calibration methodologies for autonomous recorders

The hydrophone included in an autonomous recorder may be calibrated independently using one of the methods described in previous sections only in case the hydrophone can be detached from the recorder. 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.

Pressure calibration in an air-filled closed chamber as a method of low-frequency has already been demonstrated to be applicable for autonomous recorders in the frequency range from 20 Hz to 315 Hz [13] 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.

On the other hand, free-field conditions require a medium that is free of reflecting boundaries, which is very demanding to be realised in a laboratory tank below the kilohertz range [15]. The solution adopted by partners involved in this project is to use larger volumes of water for calibration, such as a lake or a reservoir, with water depths ranging from about 20 m to about 200 m, so that a much longer echo-free time is obtained for the measurements (see Figure 7).

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 Lake Hornavan, 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 owns a facility with exclusive access to Lake Nemi near Rome, a natural lake with about 1.5 km mean diameter and about 30 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. To characterize the devices in conditions that are closer to those encountered in the field, measurements will also be performed by ISPRA in Lake Bracciano, another larger natural lake 30 km north of Rome with about 8 km diameter and about 150 m depth, that also exhibits limited climate changes and moderate noise level produced by sporadic vessel traffic. Similarly, sea trials will also be performed by TUBITAK in Marmara Sea. The above mentioned open-water sites will be used in round-robin experiments to be performed between March 2018 and November 2018.

Data measured using free-field methods in open-water sites can be contaminated by self-noise of the measuring system itself as well as 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.

Calibration methods based on diffuse sound field shall finally be investigated. This method has been demonstrated in air by DFM for microphones [16] 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 [17], [18]. 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.

5. CONCLUSIONS

The UNAC-LOW project, addressing the development of calibration standards for hydrophones and autonomous recorders for frequencies from 20 Hz to 1 kHz, has entered its main phase during which experiments will be performed by all partners either in the laboratory or in open water sites. Experimental setups for both pressure calibration methods and free-field methods have been designed and implemented in specific and overlapping frequency ranges. Preliminary tests using the air-filled coupling chamber designed for pressure method for hydrophones showed an agreement with reference calibration data obtained with free-field method. The

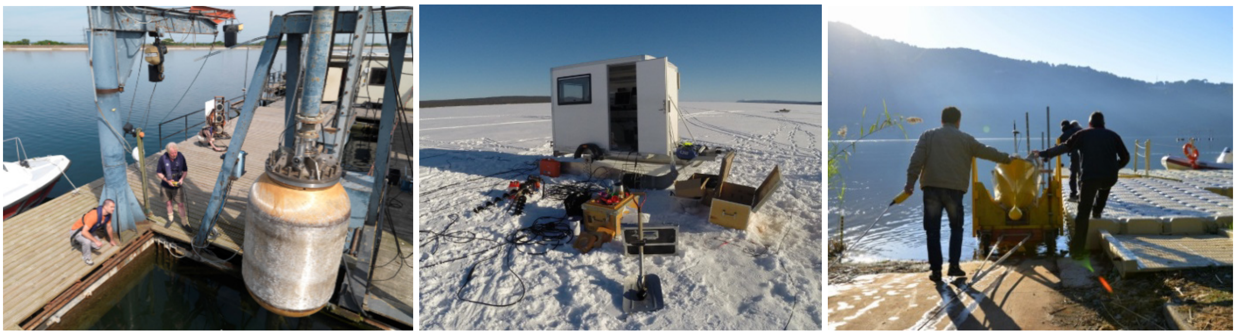


Figure 7. Open-water test sites used for calibrating autonomous recorders using free-field methods: NPL facility at Wraysbury, UK (left), FOI mobile facility at Lake Hornavan, Sweden (center), CNR test site at Lake Nemi, Italy (right).

experimental setups for calibration of autonomous recorders with pressure methods and free-field methods have been designed and the first experiments are currently under way. The compatibility of results by different methods and for different devices within stated uncertainties will be evaluated in round-robin experiments to be executed by circulating one single device, either a reference hydrophone or a reference autonomous recorder, among participants in the respective project workpackages. The experiments will take place throughout year 2018 and results shall be available near project end after first quarter of year 2019. Among project output, draft procedures and guidelines shall be produced describing the implemented calibration methods, and a common strategy for long-term sustainability of capabilities shall be defined, in agreement with requirements for the EMPIR programme. Project results shall be disseminated to the stakeholder community to ease the adoption of the developed capabilities within EU member states, for harmonised regulation and increased awareness towards preservation of the marine environment.

ACKNOWLEDGEMENT

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