FINAL PUBLISHABLE REPORT

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Coordinator: Alper BİBER, Dr, TÜBİTAK Tel: : +90 262 677 31 59 E-mail: alper.biber@tubitak.gov.tr Project website address: http://empir-unaclow.com		
Internal Funded Partners: 1. TÜBİTAK, TURKEY 2. DFM, DENMARK 3. NPL, UK	External Funded Partners: 4. CNR, ITALY 5. FOI, SWEDEN 6. ISPRA, ITALY	Internal Funded Partners:
RMG: -		

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1 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.

2 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.

3 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.

4 Results

4.1 Objective 1: Calibration of hydrophones for the frequency range between 20 Hz and 1 kHz

For this objective, the achievement of hydrophone calibration capabilities for frequencies between 20 Hz up to 1 kHz has been targeted by TÜBİTAK, NPL, DFM and FOI. The existing methods covered by IEC 60565:2006 were reviewed in order to select the low frequency hydrophone calibration methods to be developed. After selection of the methods, the design and the production of the calibration setups was done by TÜBİTAK and DFM. NPL and FOI developed their existing setups and calibration procedures. Once the calibration setups and procedures were ready for tests, round-robin comparison measurements were conducted by each partner with their setups by calibrating the hydrophones that were provided by TÜBİTAK.

The detailed works that were carried out for this objective are given below.

4.1.1 Review of Methods for Low Frequency Hydrophone Calibration

At the very beginning of the project, TÜBİTAK, NPL, CNR, DFM and FOI reviewed calibration methods covered by IEC 60565:2006 standard and selected:

- Calibration with a pistonphone method and comparison in a closed chamber method.
- Calibration in a travelling wave method and standing wave tube method

These methods were selected because they were evaluated to be suitable to realize calibrations of hydrophones with targeted uncertainty 1.0 dB in the specified frequency range of the project.

4.1.2 Design and Preparation of Calibration Setups for Hydrophones

TÜBİTAK developed pressure coupling chambers and procedures for comparison calibration of hydrophone sensitivity at frequencies from 20 Hz up to 2 kHz with uncertainty less than 1 dB. The chamber design, developed in the project, was applied for a patent through Turkish Patent and Trademark Office in April 2019. The priority date was taken with reference number TR2019/06367.

The block diagram of the setup for comparison calibrating of passive hydrophones with piezoceramic sensor is presented in Figure 1 (left). The LS1 microphone B&K 4160 serves as the reference sensor for the comparison calibration of hydrophones. Since the gain of the charge conditioning amplifier depends on the hydrophone capacitance, the amplifier gain is calibrated using the insertion voltage method together with the hydrophone under test. In the case of hydrophone calibration with an integrated pre-amplifier, its output voltage is directly measured using the voltage measuring device presented in Figure 1 (right). The measurement setup for hydrophone and noise recorder calibration is shown in Figure 2.

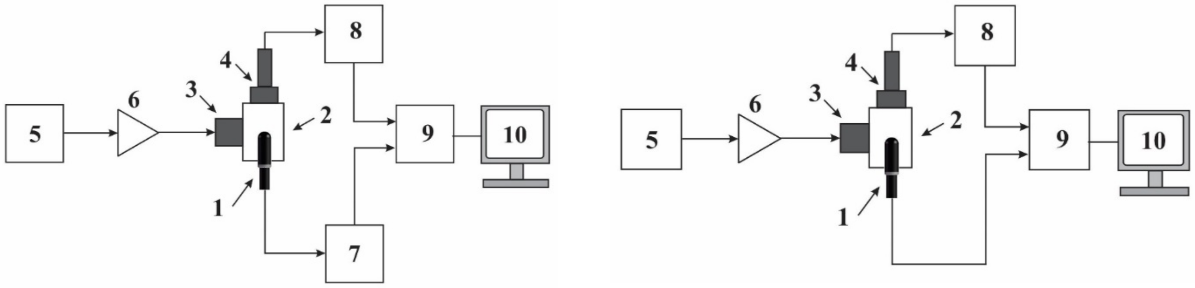

Figure 1: Setup for Comparison Calibration of Hydrophones (left: for passive hydrophone, right: for hydrophone with integrated pre-amplifier) 1) Hydrophone Under Test; 2) Coupling Chamber; 3) Actuator; 4) Reference Microphone with Preamplifier; 5) Signal Generator; 6) Power Amplifier; 7) Charge Conditioning Amplifier; 8) Microphone Power Supply; 9) 2-Channel Voltage Measuring Device; 10) PC

Figure 2: Measurement setup for the calibration of hydrophone and noise recorder

NPL developed three methods with corresponding procedures, namely:

1. Method for calibration of hydrophones using signal modelling techniques in a laboratory tank has extended the lower limit of frequency from 1 kHz to 250 Hz with an uncertainty of between 0.5 dB and 1.0 dB. NPL has developed a full uncertainty budget, and has validated the methodology by comparison with other calibration techniques.
2. Method for absolute calibration of hydrophones using a laser pistonphone in the frequency band from 20 Hz up to 160 Hz with 0.5 dB uncertainty. The general view of setup is presented in Figure 3.

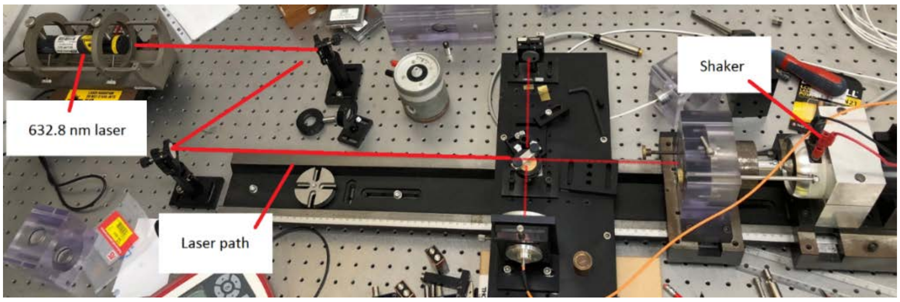

Figure 3: Bench set up showing laser, laser path and shaker

3. Method for calibration of hydrophones using comparison to a calibrated microphone in a closed chamber. This service is traceable to acoustical standards for air acoustics and is operated over the frequency range 25 Hz to 400 Hz with 0.5 dB uncertainty. The general view of setup is presented in Figure 4.

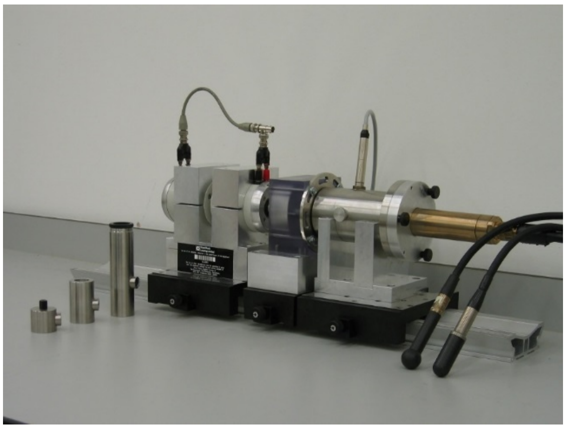

Figure 4: The NPL pistonphone chamber configured with the dual shaker drive unit

DFM developed a method for calibration of hydrophones using a coupling chamber for comparison calibration of the hydrophone with a reference set of microphones from 5 Hz up to 1600 Hz with uncertainty of between 0.3 to 1.0 dB depending on frequency. The general view of setup is presented in Figure 5.

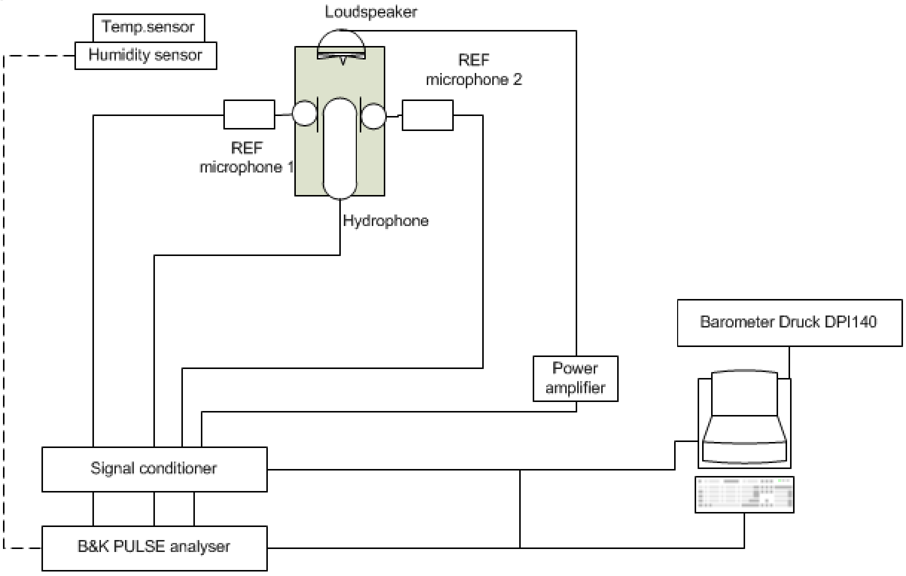

Figure 5: Schematic representation of the measurement system for hydrophones

The main feature of the chamber design is that two reference microphones are used to measure acoustic pressure inside chamber and the distance between microphones and hydrophone under the test is minimized.

FOI developed a method for calibration of hydrophones using Standing Wave Tube Method in the frequency band from 400 Hz up to 1 kHz with uncertainty of 0,8 dB. For this purpose, the USRD C100 unit with the precision holder was used. The general view of setup is presented in Figure 6.

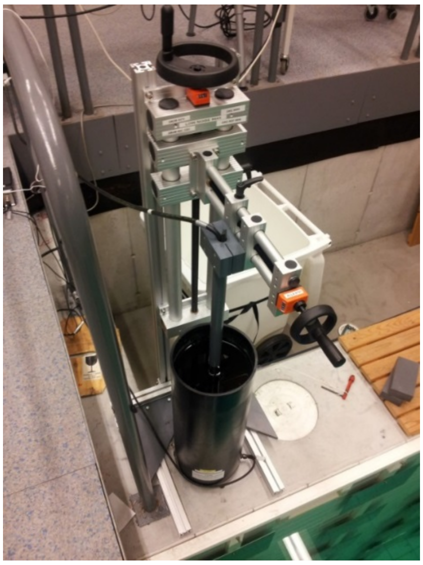

Figure 6: The USRD C100 unit with the precision holder.

The comparison calibration procedure by this setup is done accordingly: 1) the reference acoustic pressure sensor and the hydrophone under test are placed at the same point of the tube one by one, 2) and acoustic pressure at this point is the same in both cases. Ratio of output voltages of the hydrophone and reference sensor provides calculation of the hydrophone sensitivity.

4.1.3 Experiments and Validation of the Setups for Low Frequency Hydrophone Calibration.

For the validation of the developed setups and calibration procedures, round robin calibrations of B&K 8104 and B&K 8106 were done by TÜBİTAK, NPL, DFM and FOI. Before hydrophones were delivered to NPL, DFM and FOI, TÜBİTAK checked its sensitivity in a coupling chamber at frequencies below 100 Hz at which the influence of acoustic pressure inhomogeneity inside chamber is negligibly low. Figure 7 presents maximum difference in sensitivity values measured during the round robin activities.

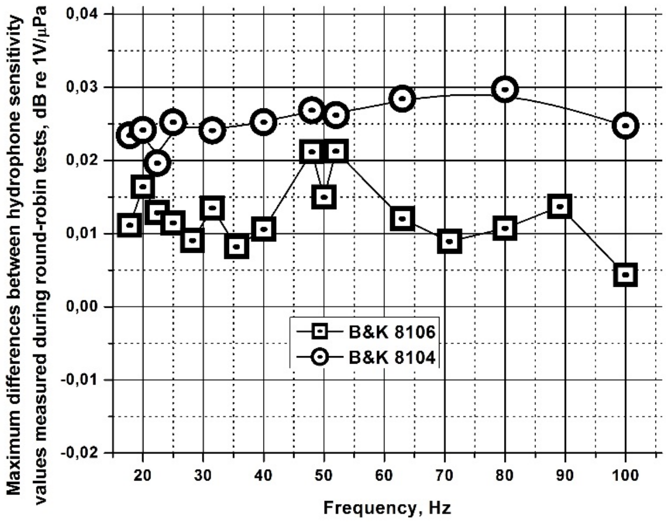

Figure 7: Stability confirmation of B&K 8104 and 8106 hydrophones used for the round robin tests.

Results of round robin calibrations at 1/3 octave central frequencies are shown in Figure 8 for B&K 8104 hydrophone and in Figure 9 for B&K 8106 hydrophone.

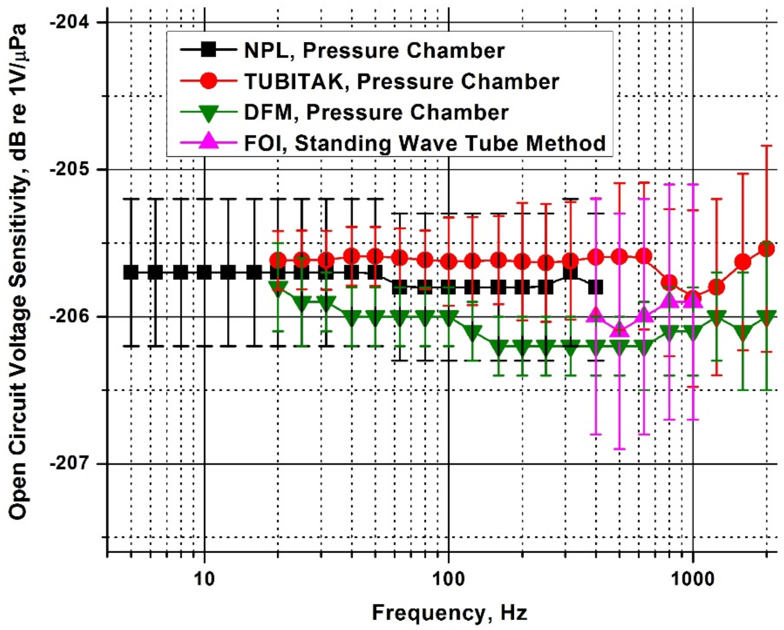

Figure 8: Plot of comparison calibration of B&K 8104 hydrophone, Ser. No 2486868

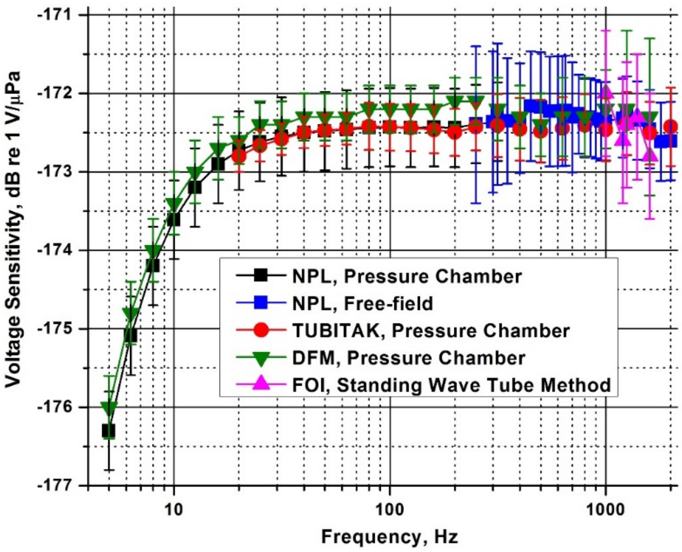

Figure 9: Plot of comparison calibration of B&K 8106 hydrophone, Ser. No 2484108

In order to validate the measurement setups, uncertainty budgets were prepared by TÜBİTAK, NPL, DFM and FOI and the calculated expended uncertainty values of performed calibrations are shown in Table 1. All uncertainties were calculated according to the guidelines provided in the ISO Guide to the Expression of Uncertainty and are expressed as expanded uncertainties (for a coverage factor k=2, and a confidence level of 95%).

Table 1. Summary of the expended uncertainties reported by each participant

Partner	B&K 8104		B&K 8106	
	Frequency Range	Calibration Uncertainty	Frequency Range	Calibration Uncertainty
TÜBİTAK	20Hz - 2 kHz	0,2 dB - 0,7 dB	20Hz - 2 kHz	0,2 dB - 0,5 dB
NPL	5Hz - 400 Hz	0,5 dB	5 Hz - 315 Hz 250 Hz - 2 kHz	0,5 dB 1 dB - 0,5 dB
DFM	20 Hz - 2 kHz	0,2 dB - 0,5 dB	5Hz - 1,6 kHz	0,3 dB - 1,0 dB
FOI	400 Hz - 1 kHz	0,8 dB	400 Hz - 1 kHz	0,8 dB

<u>Key outputs and conclusions</u>

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.

TÜBİTAK and DFM have established new calibration setups and procedures, NPL has extended calibration frequency ranges on their existing setups and FOI has worked on the validation and development of their existing setup. According to the round robin calibration data the Objective 1 is achieved with targeted expended uncertainties.

4.2 Objective 2: Calibration of autonomous noise recorders for the frequency range between 20 Hz and 1 kHz.

4.2.1 Review of Marine Autonomous Noise Recorders

At the start of the project, NPL, TÜBİTAK, CNR, FOI and ISPRA reviewed methods for the calibration and characterisation of autonomous noise recorders, namely: pressure calibration, free-field calibration and diffuse-field calibration. Also, NPL, TÜBİTAK, CNR, FOI and ISPRA summarized that underwater noise recorders of various designs may be broadly categorised into two formats: a) recorders with the hydrophone(s) rigidly attached to the recorder body, or with the hydrophone(s) attached with a short cable in close proximity to the body; b) recorders where the hydrophone(s) are separated from the recorder body with an extension cable so that they are remote form the body

In the first configuration type (a), the recorder must be calibrated as one system while the hydrophone is attached to the device, since this is how it is deployed. This can pose particular calibration challenges for free-field calibration where sound waves interacting with the body may influence the measured sensitivity. If the hydrophones are 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.

In the second configuration, although the calibration required is still that of the whole recorder system (the combination of hydrophone(s) and electronic components), because the hydrophone is deployed remotely from the recorder, this offers the possibility of calibration of the hydrophone separately from the recorder body. In some respects, this simplifies the acoustic calibration because the influence of the recorder body on the performance is minimized. 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 sum of the hydrophone and recorder sensitivities, and care must be taken to take account of any electrical loading effects

4.2.2 Design and Preparation of Calibration Setups for Autonomous Noise Recorders

NPL and TÜBİTAK worked on calibration of the noise recorders in a pressure chamber and at the same time CNR, FOI and ISPRA worked on free-field calibration methods.

Calibration of underwater noise recorders in a pressure chamber

Figure 10 shows the NPL pressure chamber configured with SM4M underwater noise recorder which was used in round robin tests between NPL, TÜBİTAK, FOI, CNR and ISPRA. The recorder hydrophone under test is inserted horizontally into the enclosed coupler chamber and sealed by an O-ring around the hydrophone body if the hydrophone is attached to the recorder unit by cable. The reference microphone is inserted into a side port with O-ring seal and typically positioned vertically above the chamber

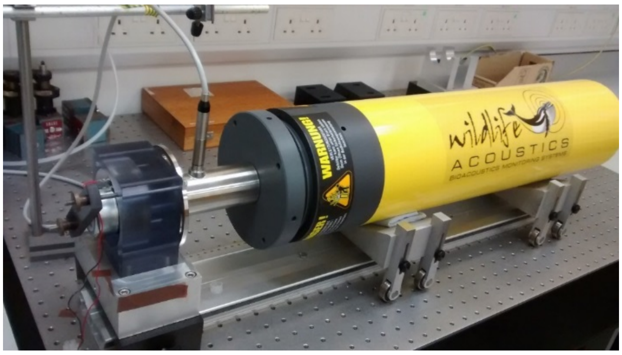

Figure 10: The NPL chamber configured with the SM4M recorder

The NPL calibration system uses a Type 7265 Dual Phase DSP Lock-in Amplifier as the oscillator sound source generator and receive signal measurement device for the microphone. The oscillator output is amplified using a power amplifier to provide a suitable drive voltage to the loudspeaker or shaker, which drives the enclosed chamber containing both the microphone and recorder hydrophone.

Both the microphone and hydrophone remain inserted into the coupler for the duration of each measurement run. The receive signal on the microphone is measured on the lock-in amplifier while the recorder is recording the same sound pressure on its memory card.

Calibration setup developed by TÜBİTAK is presented in Figure 11. The SM4M underwater noise recorder was calibrated by comparison method in laboratory condition. The hydrophone of noise recorder was inserted inside pressure coupling chamber which was designed in WP1. Reference microphone B&K 4160 was used as a reference sensor to measure acoustical pressure inside the chamber.

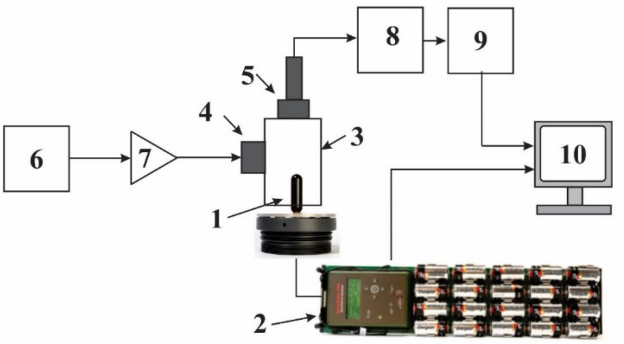

Figure 11: Setup for calibration of Wildlife Acoustics SM4M recorder at TÜBİTAK
1) Hydrophone of SM4M Recorder; 2) Song Meter SM4 with battery block; 3) Coupling Chamber; 4) Acoustic Actuator; 5) Reference Microphone with Preamplifier; 6) Signal Generator; 7) Power Amplifier; 8) Reference Microphone Power Supply; 9) Voltage Measuring Device; 10) PC

4.2.3 Experiments and Validation of the Calibration Setups for Autonomous Noise Recorders

Autonomous noise recorders, by design, are a system that takes an analogue input signal, digitises and processes the signal, then stores that digital file in form accessible by the user. At present the .wav file format has been adopted as the format of choice by the manufacturers of the recorders.

The systems use either an integrated or user changeable hydrophone as the analogue sensor. However, at no point is the user able to access the analogue signal and as such does not have the ability to interpret the recorded signal as a voltage. All accessible data is in the form of a digital representation of the sound pressure in the form of a .wav file.

For this reason, an alternative unit of calibration may be more appropriate. Specifically, a unit that does not reference the volt. Whist any alternative calibration unit will ultimately need debate by the wider user community and appropriate technical committees and standardisation groups, and alternative has been explored that provides a straightforward conversion of the .wav file back to the pressure, in Pascal, as recorded on the autonomous noise recorder.

This unit is described in this report as a sound pressure scale factor. The recorded .wav files from the recorder were analysed and the amplitudes at each frequency determined. From the recorded .wav file amplitudes and the measured sound pressures in the coupler, the sound pressure scale factor is determined as the following equation.

$$sound\ pressure\ scale\ factor = \frac{chamber\ pressure}{.wav\ file\ amplitude}$$

Note that for the .wav files, the factor represents the full-scale value at each frequency.

To obtain the actual sound pressure values from recordings made during a working deployment, the recorded data must be multiplied by the sound pressure scale factor, providing the sound pressure in Pascal.

The results for the round robin calibration of the Wildlife Acoustics SM4M underwater noise recorder in the scope of this project are given in below in Table 2.

Table 2: TÜBİTAK and NPL SM4M sensitivity calibration and sound pressure scale factor, right channel, 0 dB internal gain.

Wildlife Acoustics SM4M (0 dB internal gain)								
	TÜBİTAK		NPL		TÜBİTAK		NPL	
Frequency, (Hz)	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sound pressure scale factor (Pa)	Uncertainty (%)	Sound pressure scale factor (Pa)	Uncertainty (%)
5			-176.2	± 0.5			644.3	6
6,3			-174.0	± 0.5			503.6	6
8			-172.1	± 0.5			403.4	6
10			-170.6	± 0.5			337.7	6
12,5			-169.3	± 0.5			290.3	6
16			-168.1	± 0.5			254.1	6
20	-167.4	± 1	-167.3	± 0.5	222.2	12	232.2	6
25	-166.8	± 1	-166.7	± 0.5	207.6	12	216.2	6
31,5	-166.4	± 1	-166.2	± 0.5	198.2	12	204.8	6
40	-166.1	± 1	-165.9	± 0.5	190.8	12	196.9	6
50	-165.9	± 1	-165.7	± 0.5	186.4	12	192.1	6
63	-165.7	± 1	-165.5	± 0.5	183.8	12	188.8	6
80	-165.6	± 1	-165.4	± 0.5	181.7	12	186.2	6
100	-165.5	± 1	-165.3	± 0.5	179.7	12	184.3	6
125	-165.5	± 1	-165.3	± 0.5	179.4	12	184.3	6
160	-165.3	± 1	-165.3	± 0.5	176.1	12	183.9	6
200	-165.3	± 1	-165.3	± 0.5	175.4	12	183.5	6
250	-165.3	± 1	-165.2	± 0.5	175.6	12	182.4	6
315	-165.2	± 1	-165.2	± 0.5	175.2	12	181.9	6
400	-165.3	± 1			176.5	12		
500	-165.2	± 1			175.5	12		
600	-165.3	± 1			181.0	12		
630	-165.3	± 1			185.9	12		
650	-165.3	± 1			183.3	12		
720	-165.0	± 1			171.1	12		
800	-164.8	± 1			166.7	12		
1000	-164.5	± 1			159.6	12		

Calibration of underwater noise recorders under free-field conditions.

Two free-field calibration methods have been selected to be implemented in open water sites, by partner FOI and by CNR and ISPRA, respectively.

The first method makes use of a calibrated projector that was calibrated using the primary method of spherical wave three-transducer reciprocity. This method has been implemented by FOI in Lake Hornavan (Sweden).

The second method is that of comparison with a calibrated reference hydrophone. This method has been implemented by CNR and ISPRA in Lake Nemi (Italy). Calibration of reference hydrophone was done by TÜBİTAK using the pressure calibration method developed in objective 1. Although the comparison method does not require the projector in use to be calibrated, the projector was also used in the reciprocity calibration done by FOI, so its transmitting response (TVR) could be used to calculate independently the pressure at the receiving recorder. This allowed cross-validation of results from the two independent calibration methods.

Traceability of calibration results to primary standards is ensured by the primary method of reciprocity used in the first method, while in the second it derives from the calibrated microphone used as a reference in the pressure method. Traceability chain for both methods is shown in Figure 12.

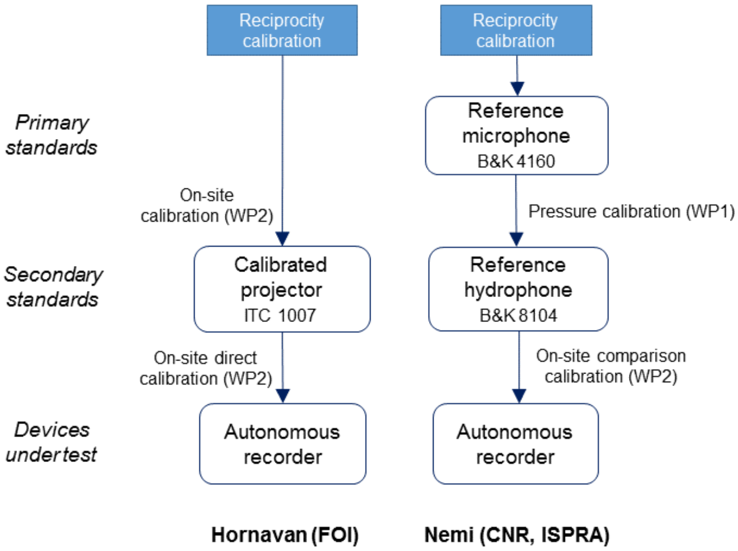

Figure 12. Traceability chain for the two implemented calibration methods. Arrows indicate calibration steps done in respective project work packages.

In the Lake Hornavan calibration, the lowest measurable frequency was 85.3 Hz. The target uncertainty of 1-1.5 dB was reached for frequencies ranging from 236.3 Hz and above. The poor response, in the lower frequencies, of the transmitting transducer was the limiting factor.

In the Lake Nemi calibration, the lowest measurable frequency was 200 Hz, due to the limited power of the transmitting amplifier and to reduced water depth not allowing free-field conditions down to 20 Hz. The target uncertainty of 1-1.5 dB was reached for frequencies ranging from 200 Hz up to 2 kHz.

The scale factor as a function of frequency for SM4M calibrated by FOI in Lake Hornavan and by CNR and ISPRA in Lake Nemi is given in Figure 13. Results obtained from the two sites agree with the stated uncertainties for frequencies up to 650 Hz, while a deviation appears for higher frequencies which is likely to depend on interference effects between the hydrophone and the recorder body, produced under different environmental conditions.

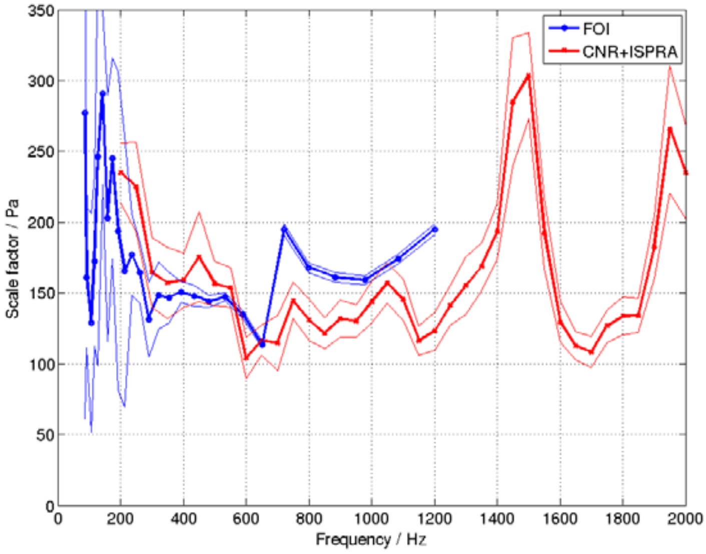

Figure 13. Results of the SM4M free-field calibration performed by FOI in Lake Hornavan and by CNR and ISPRA in Lake Nemi, in terms of a scale factor in Pa units as a function of frequency for the frequency range from 85.3 Hz to 2 kHz. Thin lines indicate upper and lower bounds defined by the expanded uncertainty evaluated for a confidence level of 95 % (*k* = 2).

The same results shown in Figure 13 are also tabulated in Table 3 below, expressed both as a sensitivity in dB re 1 V/µPa and as a scale factor in pascal, with their respective uncertainties expressed in dB and in percent. Note that frequency points do not match exactly between the two calibrations since a different spacing (logarithmic or linear) was used.

Table 3: FOI and CNR/ISPRA SM4M free-field sensitivity calibration and sound pressure scale factor, right channel, 0 dB internal gain

Wildlife Acoustics SM4M (0 dB internal gain)								
Frequency, (Hz)	FOI		CNR/ISPRA		FOI		CNR/ISPRA	
	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sound pressure scale factor (Pa)	Uncertainty (%)	Sound pressure scale factor (Pa)	Uncertainty (%)
85.3	-168.9	± 7.2			277.0	78		
92.5	-164.1	± 2.7			161.0	31		
106.3	-162.2	± 5.4			129.0	60		
116.3	-164.7	± 3.1			172.7	35		
129	-167.8	± 5.4			246.0	60		
142.5	-169.3	± 1.9			290.7	22		
157.9	-166.1	± 3.8			202.7	43		
174.2	-167.8	± 2.5			245.0	29		
192.8	-165.7	± 5.2			193.7	58		
200			-167.4	± 0.7			235.0	9
213.4	-164.4	± 5.2			165.3	58		
236.3	-165.0	± 1.4			177.0	16		
250			-167.0	± 1.2			224.8	14
261.4	-164.3	± 1.2			164.3	13		
289.3	-162.4	± 1.7			131.3	20		
300			-164.3	± 1.2			164.6	15
320.4	-163.4	± 1.4			148.3	16		

Wildlife Acoustics SM4M (0 dB internal gain)								
Frequency, (Hz)	FOI		CNR/ISPRA		FOI		CNR/ISPRA	
	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sensitivity (dB re 1 V/µPa)	Uncertainty (dB)	Sound pressure scale factor (Pa)	Uncertainty (%)	Sound pressure scale factor (Pa)	Uncertainty (%)
350			-163.9	± 1.3			157.2	16
354.5	-163.3	± 1.0			146.7	12		
392.3	-163.6	± 0.4			150.7	5		
400			-164.0	± 1.0			159.0	12
434.4	-163.4	± 0.4			148.0	5		
450			-164.9	± 1.4			175.5	18
480.9	-163.2	± 0.2			144.0	3		
500			-163.9	± 0.8			156.5	10
532.3	-163.3	± 0.2			147.3	2		
550			-163.7	± 0.8			153.8	9
589.2	-162.6	± 0.1			134.7	2		
600			-160.3	± 1.2			104.0	14
650			-161.3	± 0.7			116.6	9
652.1	-161.1	± 0.1			113.3	2		
700			-161.2	± 1.3			114.4	17
722.5	-165.8	± 0.1			194.7	2		
750			-163.2	± 0.8			144.6	9
799.2	-164.5	± 0.1			168.0	2		
800			-162.3	± 0.9			130.9	11
850			-161.7	± 0.7			121.6	9
884.6	-164.1	± 0.1			161.0	2		
900			-162.4	± 0.8			131.8	10
950			-162.3	± 0.7			130.1	9
979.3	-164.0	± 0.1			159.0	2		
1000			-163.1	± 0.9			143.6	10
1050			-163.9	± 0.8			156.9	9
1084.1	-164.8	± 0.1			174.0	2		
1100			-163.2	± 0.8			145.4	10
1150			-161.3	± 0.7			116.3	9
1200	-165.8	± 0.1			195.0	2		
1200			-161.8	± 0.9			123.0	11
1250			-163.0	± 0.9			141.1	10
1300			-163.8	± 1.1			155.0	13
1350			-164.5	± 0.8			168.7	10
1400			-165.7	± 0.8			193.5	10
1450			-169.1	± 1.3			284.8	16
1500			-169.6	± 0.8			303.6	10
1550			-165.7	± 1.1			192.2	13
1600			-162.2	± 0.9			129.5	11
1650			-161.0	± 0.7			112.6	9
1700			-160.7	± 0.8			108.2	10
1750			-162.1	± 0.8			126.8	9
1800			-162.5	± 0.9			133.7	10
1850			-162.5	± 0.7			134.0	9
1900			-165.2	± 1.0			182.6	12
1950			-168.5	± 1.4			265.4	17
2000			-167.4	± 1.2			235.0	14

Key outputs and conclusions

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 unfavorable 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.

TÜBİTAK and NPL developed calibration setups and procedures for laboratory calibration, FOI, CNR and ISPRA developed calibration setups and procedures for free field calibration for autonomous noise recorders. According to the round robin calibration data the Objective 2 is achieved for laboratory calibration of autonomous noise recorders. Guidelines for the calibration of autonomous noise recorders has been prepared for free field calibration as a result of this project.

4.3 Objective 3: Individual strategy for each partner for long-term operation of the developed measurement capabilities

NPL, TÜBİTAK, DFM, FOI and CNR developed an individual strategy for the long-term operation of the research and calibration capabilities developed within the project. NPL, TÜBİTAK, DFM and FOI developed a strategies for offering calibration services from their established facilities to the used community in their own country as well as in neighbouring countries.

Key outputs and conclusions

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.

DFM has developed a system able to calibrate hydrophones B&K type 8104 and 8106 in the frequency range from 2 Hz and up to 1 kHz. The system is based on comparing the hydrophone against two reference microphones simultaneously in an optimised comparison coupler. The design of the coupler can be also used for other types of hydrophones as needed. DFM's policies indicate that new services must be accredited or in the process of being accredited before offered to customers. Final versions of the procedures are being prepared, and are expected to be submitted to the accreditation body by the December 2019. This is to be evaluated in the forthcoming accreditation visit by DANAK in January 2020.

TÜBİTAK, NPL, DFM, FOI and CNR have developed their individual strategies for the long-term operation of research and calibration capability developed within the project and objective 3 has been achieved.

5 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.

6 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