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Open-water free-field calibration of an autonomous underwater noise recorder for frequencies below 1 kHz

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Abstract **– The results of the free-field calibration of an autonomous underwater noise recorder performed in an open-water test site are presented, as part of the output of the "UNAC-LOW" metrology research project which aimed at developing low-frequency calibration methods for hydrophones and autonomous recorders. The calibration was done for frequencies ranging from 200 Hz to 2 kHz by comparison with a reference hydrophone which was calibrated by another project partner using a closed-chamber pressure method. Calibration uncertainties were between 0.7 dB and 1.7 dB, and good agreement up to about 550 Hz was found with results obtained by another project partner using a different setup. Two different mooring solutions are presented and discussed for the device under test. Possible ways to extend the low frequency limit are discussed, to comply with requirements set in current EU regulation for monitoring of low-frequency continuous underwater noise.**

I. INTRODUCTION

In the past decades there has been an increased need for absolute measurements of sound in the seas driven by ongoing concerns about the environmental impact of human activity [1, 2]. In order to be meaningful, such absolute measurements require traceability to agreed standards [3]. However, such standards are not readily and widely available for acoustic frequencies below 1 kHz, in which anthropogenic sources of most environmental concern – primarily, commercial shipping and, secondarily, seismic exploration – radiate most of their sound energy [4].

Therefore, an urgent need exists for traceable calibration of the instrumentation used for low frequency underwater noise measurements, driven by regulation and by the increasing commercial availability of autonomous recorders for long term noise monitoring at sea [5].

Regarding vessel noise, which is by far the loudest and most ubiquitous component of low-frequency anthropogenic noise, its impact on the coastal marine environment is driving port authorities to include underwater noise levels in the criteria to establish harbour fees to any vessel for each harbour call [6]. Measures, such as voluntary ship slowdowns, lateral displacements, and ship quieting options are currently under consideration in authority-led initiatives aiming at preserving marine habitat [7]. Addressed to the ships in service, some measurement procedures have been developed which are able to provide additional class notations useful to evaluate the environmental impact originated by their own underwater radiated noise in different operating conditions [8, 9].

Motivated by this scenario, the "UNAC-LOW" [10, 11] metrology research project was funded by EURAMET under the EMPIR programme 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 aimed at developing the scientific and technical research capabilities in the field within Europe, providing 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) [12].

The "UNAC-LOW" project lasted 3 years between May 2016 and April 2019. Six EU partners participated from 5 States facing all major European seas: TÜBİTAK (Turkey, lead partner). NPL (UK), DFM (DK) CNR (I), ISPRA (I), FOI (SE).

Within "UNAC-LOW", traceable measurement capabilities have been developed by each partner for calibration of hydrophones and autonomous underwater acoustic noise recording systems for frequencies below 1 kHz, including the 63 Hz and 125 Hz third-octave bands required by the EU MSFD. New traceable calibration methods have been developed for autonomous noise recorders for which there are no established calibration methods. Developed methods include closed-chamber pressure methods (developed by TÜBİTAK, NPL, and DFM) and free-field, open-water methods (developed by CNR, ISPRA, and FOI). Open-water methods have the advantage over pressure methods that the entire system (including both the hydrophone and its main body) is exposed to the incident sound wave, so that possible diffraction and interference effects are accounted for in the response. Such effects typically introduce wide fluctuations in the frequency response in the kHz range, especially for units with their hydrophone fixed in proximity of the recorder body.

II. EXPERIMENTAL SETUP

A. Test site

The calibration was performed in January 2019 in Lake Nemi near Rome (see Fig. 1), which has been used for decades by CNR-INM (formerly INSEAN) as outdoor maneuvering basin for unmanned self-propelled free-running surface ship model tests. This site has been recently confirmed to possess excellent features as an open-water acoustic test site, due to its exceptionally low level floor noise. The lake has no water inlet or outlet, is about 1.5 km in diameter with maximum depth of 33 m and silt bottom. No other human activities are present.

A suitable location was selected to perform measurements near lake centre, with a flat bottom of about 28 m depth. During the campaign, the following environmental conditions were recorded:

- Outdoor temperature ranging from about 4 °C to about 10 °C;
- Wind ranging from 0 to a few m/s, with surface wave height up to few cm only;
- Water temperature (7.7 ± 0.1) °C measured at 10 m depth, with stable results and isothermal vertical profile between 1 m and 15 m depth;
- Water salinity (0.2 ± 0.1) part per thousand.

Fig. 1. Lake Nemi open-water test site.

Fig. 2. Wildlife Acoustics SM4M autonomous recorder calibrated within the UNAC-LOW project.

B. Device under test

The device to be calibrated was a Wildlife Acoustics SM4M autonomous recorder (see Fig. 2), which was circulated among participants in a round-robin exercise from early 2018 until early 2019. This unit exhibits a fixed hydrophone in close proximity to the main body, so considerable diffraction and interference effects were expected in its frequency response.

Two different recording configurations were tested with different sampling rate and internal gain settings, as reported in Table 1.

Table 1. SM4M configurations used.

Config. N.	Sampling rate	Internal gain
1	96 kHz	0 dB
2	24 kHz	+12 dB

As with most autonomous recorders, the SM4M stores the recorded signal in uncompressesd WAV audio files. Files are stored in an SD card which may be taken out of the unit and read on any PC using a variety of data processing software. A disadvantage of this data storage method is that the unit needs to be opened and turned off before datafiles can be retrieved. While suitable for long-term operations, such method is less practical for quick checks and calibration.

C. Device positioning and mooring

A floating platform was moored at the selected location to host all equipment and to suspend the projector P (ITC 1007), the reference hydrophone Ref (Brue&Kjaer 8104), and the SM4M (see layout in Fig. 3). The SM4M was fixed near the end of the 7 m long side using two methods:

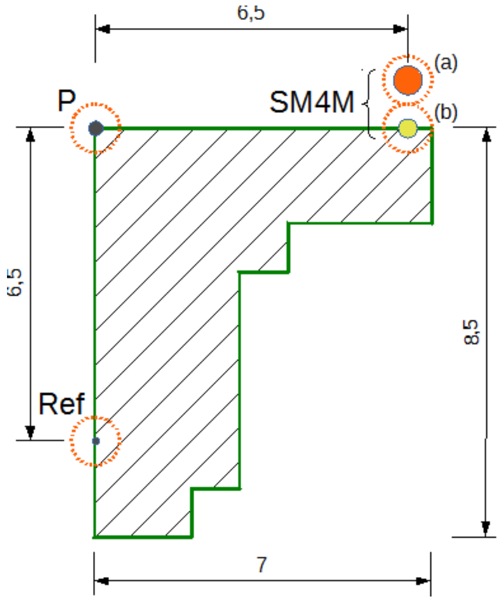

Fig. 3. Floating platform layout with positions of projector P, reference hydrophone Ref, and recorder SM4M: (a) and (b) show different mooring locations. Dimensions are in meters.

- using a 60 cm diameter floating buoy (Benthos sphere) linked to the platform side by a 1 m long line,;
- suspending the SM4M directly from the platform side using a piece of V-shaped elastic cord.

Both methods allowed to physically decouple the recorder from platform, to prevent platform noise to be picked up in the recording. For the same reason, the reference hydrophone was also mounted using elastic cords inside a suspension cage.

The acoustic centers of P, Ref and SM4M were placed at a common depth of (9.50 ± 0.05) m, limited by the cable length of Ref (10 m) to have a dry connection at the end of cable. Cable length was the limiting factor for the low frequency limit, as with this geometry the reflection from the free surface governs the maximum allowable free-field time.

The P-Ref distance was measured from the points where their cables entered the water surface. The distance to SM4M could only be roughly estimated when suspended from buoy, and more precisely when connected to platform. This had an impact on the overall calibration uncertainty, with an additional 0.4 dB when using floating buoy mooring. Measured distances are reported in Table 2.

Table 2.Distance from projector to recorder using different mooring solutions..

Mooring type.	Distance	Error
Floating buoy	7.0 m	0.2 m
Platform suspended	6.65 m	0.05 m

No attempt was made to evaluate the azimuthal orientation of all devices once they were positioned underwater, and omnidirectional response is assumed for all in the frequency range of interest. This also makes the 90° angular separation of Ref and SM4M with respect to P irrelevant, and considerably simplifies the operations with respect to the classical implementation of a comparison method, based on physical substitution of the two receivers. The omnidirectional response approximation is handled by adding one term in the uncertainty budget evaluation (whose appearance is however balanced by the absence of another term dealing with projector stability, no longer necessary as propagation towards both receivers is simultaneous).

D. Measurement setup

The calibration was performed using the comparison method with an uncalibrated projector P and a calibrated reference hydrophone Ref. The latter was calibrated by lead project partner using a novel closed-chamber pressure method developed in a separate project work package. Ref calibration data were available in the frequency range from 20 Hz to 2.5 kHz.

For each frequency point, a series of sinusoidal bursts of integer number of periods were emitted by P with repetition rates ranging from 1 to 1.5 s. Averaging was performed on received signals over each series, to increase signal/noise ratio. Frequency was stepped linearly in two different overlapping ranges:

A. from 500 Hz to 5 kHz with 100 Hz step
B. from 200 Hz to 2 kHz with 50 Hz step

Range A with configuration 1 (see Table 1) was used in one measurement sessions, while range B with configuration 2 was used in two more sessions. Adverse weather conditions allowed no further sessions to be performed: therefore, the uncertainty term due to repeatability could only be evaluated up to 2 kHz.

Transmit signals were generated and receive signals were acquired using a National Instruments PXI system equipped with a 24-bit multifunction board (PXI-4461). Sampling rates for the analog input and output was set to 192 kHz, either 2 or 4 times the sampling rate of the SM4M according to its configuration.

The projector P was fed by a fixed gain (50 x) power amplifier (Falco WMA-300). Signals from Ref hydrophone were passed through a low-noise preamplifier (Stanford Research SR560) with highpass filter set at 10 Hz and variable voltage gain between 100 and 1000.

Due to the limited power capability of the transmitting amplifier (50 W) it was necessary to compensate for the reduced acoustic output of the projector at lower frequencies using different receiving preamplifier gains for each range to maintain an acceptable signal/noise ratio.

The AC electric current flowing through P was measured by means of a current transformer to verify no saturation or clipping was present.

Free-field time for the given transmit/receive geometry and sound velocity (about 1438 m/s with given temperature, salinity and depth) was approximately 9 ms. This allowed to transmit tone bursts with nearly two cycles at 200 Hz up to about 45 cycles at 5 kHz.

All measuring instruments were powered by a silent power supply featuring a 40 Ah battery and 220 VAC, 500 W inverter allowing about three hours' endurance.

III. DATA PROCESSING

Signals received by Ref could be easily identified and processed, as they had been simultaneously acquired and synchronized with transmit P signals. On the other hand, the corresponding signals in files recorded by SM4M needed to be identified and processed manually.

Once all valid pings in SM4M files were identified, they were bandpass filtered to reduce noise, and each ping was aligned in time with other repeated pings for each frequency point. The amplitudes were then calculated using a sinusoidal fit routine and averaged.

In parallel, Ref signals were first pre-processed to remove electric noise caused by e.m. interference ("cross-talk") of the transmit signal, and their amplitudes were calculated using the same method.

The output of these two processing streams were input to a final calculation of calibration results in terms of an output quantity named Scale Factor (SF). Such quantity was introduced to avoid reference to volt units, which is inherent in the traditional definition of receiving sensitivity and loses its validity in case of devices with digital output. Such scale factor is the conversion factor between dimensionless readings in the output digital audio file and pressure in pascal; it is expressed in pascal units and is numerically equal to the inverse of an "equivalent" sensitivity M expressed in usual linear units:

$$\mathrm{SF} = 1 / M \, . \qquad (1)$$

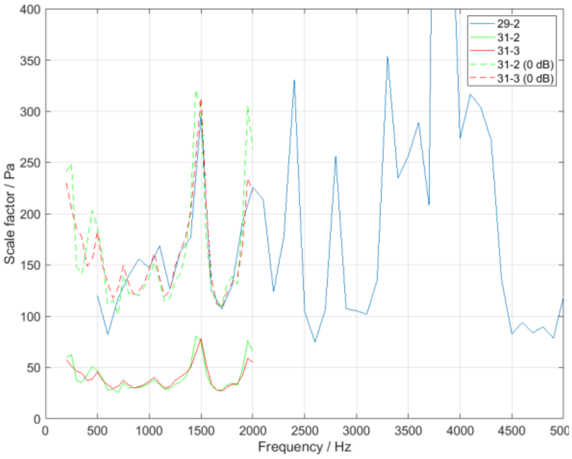

Fig. 4. SM4M calibration results in terms of scale factor in Pa units as a function of frequency for the three valid measurement sessions in the frequency range from 200 Hz to 5 kHz. Dashed lines show data obtained for SM4M configuration with +12 dB gain normalized to 0 dB internal gain, to ease comparison with the other series.

In the present case, the equivalent receiving sensitivity M was first calculated using the classical formula for the comparison method modified to account for different P-SM4M and P-Ref distances assuming spherical spreading with $1/d$ attenuation with distance [13]:

$$M_{\mathrm{H}} = M_{\mathrm{Ref}} \, (U_{\mathrm{H}} / U_{\mathrm{Ref}}) \, (d_{\mathrm{PH}} / d_{\mathrm{PRef}}) \, K_C \, , \qquad (2)$$

where subscript H applies to the SM4M, M_{Ref} is Ref calibration data, U is the received signal amplitude (ranging from -1 to +1 for the SM4M audio file), d is distance and K_C is a correction factor for capacitive loading of the preamplifier by Ref.

IV. RESULTS AND DISCUSSION

Calibration results, in terms of Scale Factor SF in pascal, for each of the three calibration sessions are shown in Fig. 4 for frequencies from 200 Hz up to 5 kHz. Positive peaks, equivalent to negative peaks in the equivalent sensitivity response, indicate that interference occurs due to reflections caused by the recorder body which is physically only a few cm away from acoustic center of the integral SM4M hydrophone.

Repeatability – and therefore uncertainties – could only be evaluated up to 2 kHz for which at least two session dataset were available. Averaged results in this narrower frequency range are shown in Fig. 5.

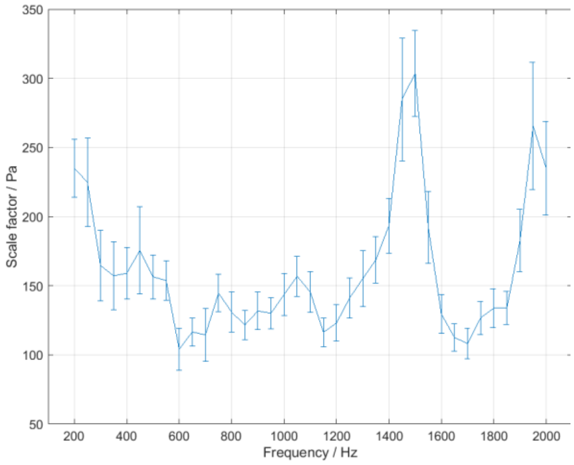

Fig. 5. Averaged SM4M calibration results in terms of scale factor in Pa units as a function of frequency for the frequency range from 200 Hz to 2 kHz with at least two measured values available. Error bars indicate the averaged expanded uncertainty for a confidence level of 95 % (k = 2).

The reported uncertainties were calculated for a 95 % confidence level (k = 2) [14]: values were between 0.7 dB and 1.7 depending on both frequency and on the mooring method used. Mooring with floating buoy caused increased positioning error, thus increased uncertainty.

The upper 2 kHz limit is in agreement with project requirements: nevertheless, the implemented method has a fairly broad scope and can be used at least in principle up to several tens of kHz with no substantial modifications.

On the other hand, the low frequency limit is substantially higher than the target set in project objectives (20 Hz). Reasons for this discrepancy are both physical – the limited water column height of the lake – and technological – the limited signal/noise ratio achievable with the present instrumentation. Overcoming the latter, i.e. using upgraded instrumentation, the low limit may be pushed down to about 100 Hz, assuming signal amplitudes to be safely evaluated using one single sinusoidal cycle only. However, to maintain true free-field conditions down to the 20 Hz low frequency limit it is necessary to have access to larger water volumes than the present one. With this aim, a 5 times deeper lake (Lake Bracciano) was selected and preliminary tests have been performed to check its suitability in terms of background noise. Work is currently under way to determine how to adapt the present setup to this larger lake, which would enable to extend the frequency range of measurements down to at least 50 Hz, if not further down. This would enable to perform free-field calibration of measuring instrumentation in full compliance with the Marine Strategy Framework Directive, which requires to monitor low frequency continuous noise in the 63 Hz and 125 Hz third-octave bands.

A comparison of results presented here was done with calibration results obtained in the frequency range from 200 Hz up to 1200 Hz by another project partner with the same device, using a differernt method (reciprocity) in a different site (Lake Hornavan, an ice capped lake in Northern Sweden). The comparison showed fairly good agreement for frequencies between 200 Hz and 550 Hz, for which differences were ranging between 0.5 dB and 1.5 dB. For higher frequencies the deviations were larger, up to 3-4 dB, and may be attributed to different behavior of the recorder in different environmental conditions for frequencies close to one of the peaks in the response due to interference by the recorder body.

V. CONCLUSIONS

Within the «UNAC-LOW» metrology research project, ended in April 2019, the free-field calibration of an autonomous recorder was performed in an open-water test site (Lake Nemi) in the frequency range from 200 Hz to 5 kHz, using the comparison method with a calibrated reference hydrophone. Repeat measurements, available for frequencies up to 2 kHz, allowed to evaluate measurement uncertainty to be in the range between 0.7 dB and 1.7 dB, depending on frequency and on the method used for mooring the recorder – which in turn influenced its positioning error. Results were expressed in terms of a output quantity named Scaling Factor, in pascal units, which is numerically equal to the inverse of an equivalent sensitivity and is more appropriate for a digital device since it bears no reference to an output quantity in volt.

A comparison with results obtained by another project partner, who used a different setup in a different site different environmental conditions, generally showed good agreement, with deviations exceeding uncertainties only for frequencies above 600 Hz where the response starts to show interference peaks due to recorder body resonances.

The results presented here confirm that the CNR-INM test site of Lake Nemi is a suitable site to perform free-field calibration of underwater equipment (including hydrophones and autonomous recorders) in the frequency range from 200 Hz up to several tens of kHz (with present instrumentation), and potentially from 100 Hz up (by employing upgraded instrumentation), with uncertainties ranging from 1 dB to 1.5 dB.

The availability of Lake Nemi test site and the confirmation of its suitability as a low-frequency acoustics calibration site is a first step towards establishing long-term services for testing and calibration of instrumentation used to perform monitoring of underwater noise in 63 Hz and 125 Hz third-octave bands, as required by the Marine Strategy Framework Directive.

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