CHALLENGES IN THE CALIBRATION OF MARINE AUTONOMOUS ACOUSTIC RECORDERS

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Abstract: *There has been an increasing use of autonomous acoustic recorders for absolute in-situ measurement of sound in the marine environment. The technology has developed rapidly utilising recent improvements in mobile microprocessors and data acquisition systems, and currently there are a number of commercial off-the-shelf units available to the user. Whilst offering the enhanced ability to monitor acoustic signals autonomously for extended periods, such recorder units introduce a number of measurement and calibration challenges in addition to those associated with the calibration of individual hydrophones. In this paper, methodologies are presented for the calibration and characterisation of autonomous recorders to determine the key acoustic performance characteristics, including the absolute system sensitivity as a function of frequency and direction. Consideration is given to effects due to the proximity of the recorder body to the measuring hydrophone on the frequency and directional response of the overall system. The need for enhanced traceability is particularly acute at frequencies below 1 kHz where high-amplitude anthropogenic sources of greatest concern radiate much of their sound energy. A discussion is provided of the EU EMPIR UNAC-LOW project, and how the work described here feeds into a European initiative to provide improved traceability and more robust metrology infrastructure to catch up with the rapidly evolving legislative framework.*

Keywords: *calibration, acoustic recorders*

1. INTRODUCTION

A common driver for the measurement of sound in the ocean is the requirement for monitoring marine noise in support of regulation for the protection of the marine environment. For absolute measurements of sound, the measurements must be traceable to common standards, with the performance of the measurement system one of the crucial factors governing the quality of the measured data [1]. There has been increasing use of autonomous acoustic recorders in recent years for absolute in-situ measurement of sound in the marine environment [2]. The technology has developed rapidly utilising recent improvements in microprocessors and data acquisition systems, and currently there are a number of commercial off-the-shelf units available to the user. Whilst offering the enhanced ability to monitor acoustic signals autonomously for extended periods, such recorder units introduce a number of measurement and calibration challenges in addition to those associated with the calibration of individual hydrophones. These include the need to treat the autonomous acoustic recorder as a complete system, providing a traceable calibration which includes the hydrophone, hardware, signal processing, the digital-to-analogue conversion, and software processing used to produce the sound data file. This requires significant modifications to the standardised calibration procedures traditionally used for individual hydrophones. There is a need to provide the traceability for the absolute measurement of sound in the ocean using autonomous recorders so that noise monitoring strategies and in-situ source characterisations are underpinned by robust metrology. The need for enhanced traceability is particularly acute at frequencies below 1 kHz where high-amplitude anthropogenic sources of greatest concern radiate much of their sound energy.

2. CONSIDERATIONS IN CALIBRATION OF ACOUSTIC RECORDERS

2.1 Challenges in the calibration of acoustic recorders

A number of challenges are presented by the calibration of marine autonomous acoustic recorders [3,4]: (i) typically, no access to the individual components of the autonomous noise recorders - a “black-box” system calibration often being required; (ii) no access to “live” analogue signals that are typically available in traditional transducer calibration procedures, thus requiring post processing of a “recording” acquired during the calibration (makes some measurements difficult, eg directivity); (iii) for recorders with hydrophones fixed to the body, free-field performance may be affected by body resonances in the frequency range 300 Hz to 1 kHz, and also (at kilohertz frequencies) by diffraction and reflection of incident sound waves by the recorder body; (iv) difficulties in determining key performance metrics such as self-noise (for measurement of low ambient levels) and dynamic range (for high amplitude signals).

2.2 Configurations for recorders

Several configurations exist for marine autonomous acoustic recorders, 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; or (b) recorders where the hydrophone(s) are separated from the recorder body with an extension cable so that they are remote from the body. In both of the above configurations, shown schematically in Figure 1, the hydrophones either may or may not be detachable from the body, depending on whether the cable is hard wired to the recorder body, or attached via a detachable electrical connector. 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

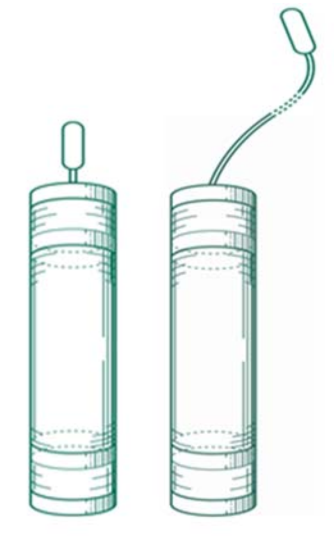

Fig. 1: Two typical recorder configuration categories

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 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 sum of the hydrophone and recorder sensitivities, and care must be taken to take account of any electrical loading effects. Another configuration involves a so-called "digital hydrophone", where the hydrophone has on-board preamplification and ADC functionality and may have some on-board recording capability, with the digitised signal also transmitted via cables for storage and/or further processing (again, with no access to analogue signals)

2.3 Calibration principles

The calibration of hydrophones is the subject of a comprehensive international standard, IEC 60565:2006, covering frequencies between 0.01 Hz and 1 MHz [5], and also an American national standard over nominally the same frequency range: ANSI/ASA S1.20:2012 [6]. Although there are, at present, no standards describing the calibration procedure for underwater autonomous acoustic recorders, the performance testing and characterisation of underwater autonomous sound recorders may be undertaken using the same basic principles that underpin the methods for hydrophone calibration.

Full system calibration versus separate hydrophone calibration

Since the end user requirement is for a full system calibration so that the acoustic data recorded by the system may be "calibrated" in full, this must be the objective of any calibration method. For systems where the hydrophone may be detached from the recorder, the hydrophone may be calibrated independently [5 -7]. Note that this latter scenario is typical of certain types or recorder which are compatible with a range of separate hydrophone models available from commercial hydrophone suppliers.

No access to live analogue signals

In general, the lack of access to "live" analogue signals requires post processing of a "recording" acquired during the calibration. This means that during calibration, instantaneous processing of signals is not possible, and instead a recording is made of the acoustic signal insonifying the recorder hydrophone. This requires modifications to the typical measurement procedure to allow post-processing of the acoustic signal waveforms, and prevents common signal acquisition techniques such as real-time coherent averaging of time domain signals. Note that the above post-processing is required even if the recorder electronics are being calibrated by electrical signal injection techniques.

Free-field calibration and the influence of the recorder body

For scenarios where the hydrophone may be detached from the recorder, the free-field calibration of the hydrophone becomes relatively straightforward and is covered by existing standards [5]. For recorders with hydrophones fixed to the body, free-field performance may be affected by body resonances in the frequency range 300 Hz to 1 kHz, and is affected at kilohertz frequencies by diffraction and reflection of incident sound waves by the recorder body. Free-field calibration poses additional difficulties from: (i) achieving free-field steady-state conditions in test tanks of limited dimensions due to limitations on available echo-free time; and (ii) suitable mounting of the recorders in the required orientation without the mounting or clamping method influencing the diffraction around the body or the resonances inherent within the recorder body.

3. LOW-FREQUENCY PRESSURE CALIBRATION

There are well stablished methods for the pressure calibration of hydrophones at low frequencies [5], and these may be applied to recorders. Here, only the hydrophone is exposed to the sound field. The pressure calibration is performed in an enclosed volume (chamber), where the dimensions of the chamber are very small compared to the acoustic wavelength. In such a situation, the sound pressure may be regarded as constant throughout the chamber [5-7]. Typically, this is a relative calibration method where the sensitivity of the acoustic system under test is determined by comparison to a calibrated reference device, which may be a hydrophone or microphone [5]. Sometimes, the chamber is air-filled, containing both a microphone and the hydrophone, which are simultaneously exposed to the same acoustic pressure. For an air-filled chamber, the volume may be driven by a piston or speaker driver. The method is suitable for calibrations at low frequencies, and should be able to cover the range 5 Hz to 300 Hz, where the sensitivity of a hydrophone is the same in air as in water for small acoustically-hard hydrophones. The method may be used as an absolute method where the pressure in the chamber is determined from the displacement of a piston source [8.9], or as a relative method where the hydrophone is calibrated with reference to a hydrophone or microphone. Alternatively, it is possible to use part-air and part-water filled chamber, with a piston used to drive a small air cavity above the water and a reference microphone used to monitor the pressure in the air cavity. The sound pressure is the same in both air and water, and such a chamber can operate at higher frequencies than a purely air-filled chamber [5,7]. The applicability of using an air-filled chamber for pressure calibrations by comparison as applied to underwater autonomous marine recorders has been previously demonstrated [3,4]. The set up includes mounting the recorder hydrophone in the coupler along with a reference microphone. Both acoustic systems are subjected to tonal signals over the frequency range between 20 Hz and 315 Hz. The microphone signal measurements are made in real time in response to the individual tonal signal stimulus, while the recorder is set to record the entire frequency sweep, as non-compressed audio files. These are analysed in post-processing and the peak-to-peak voltage levels at each frequency are determined. The calibration of the entire system is then determined by dividing the recorded signal amplitude

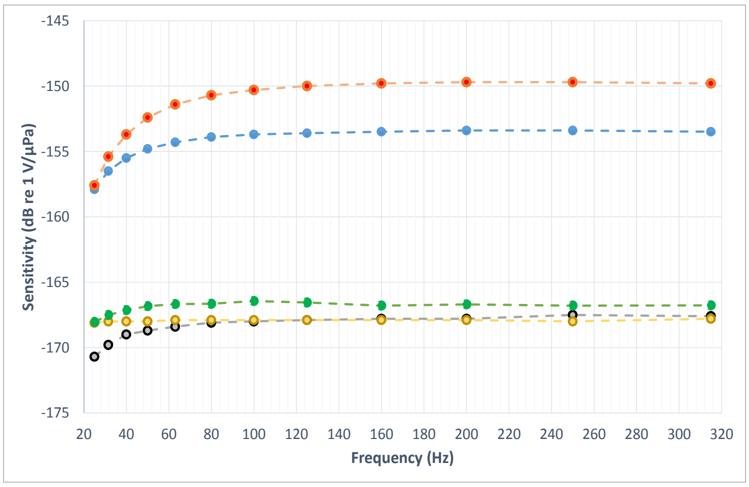

Fig. 2 Low-frequency calibration results for commercially available recorders

by the known acoustic pressure. The sources of uncertainty in the method include the calibration of the reference microphone (or hydrophone); uncertainty in electrical measurements (components may be minimised if voltage ratios are measured using same measuring channel); the gain of any hydrophone amplifiers used; lack of uniform acoustic pressure in the chamber at high frequencies; thermal conduction between air and chamber walls at very low frequencies; air leakage around piston and venting of the microphone diaphragm, at very low frequencies. If the method is used in an absolute sense with a piston driver, the uncertainties due to the reference device are eliminated but there are additional sources from measurement of piston displacement, piston area and chamber volume. The high frequency limit is caused by the non-uniform pressure field in the chamber when radial and length modes become established.

Figure 2 shows the results of calibration of a number of commercially available recorders using the above method. The results show varying degrees of low frequency roll-off in response due to high-pass electronic filters with different settings. Some recorders have the capability for the roll-off of the filters to be set by the user using hardware or software controls.

4. FREE-FIELD CALIBRATION

Free-field conditions ideally require a medium that is free of reflecting boundaries (or scattering objects) such that only outgoing waves from the source are present. However, calibrations are commonly undertaken in laboratory test tanks which are quite reverberant [5,7]. To enable free-field acoustic conditions to be realised, time-gated signals are often employed to make measurements at discrete acoustic frequencies. In the conventional arrangement, measurements are made on the steady-state portion of the received signal, with time-gating techniques used to isolate the direct-path signal from reflections from the tank boundaries and the water surface. In such measurements, the steady-state signal available for analysis is limited in time both by the arrival of boundary reflections, and by start-up transients caused by the resonant behaviour of the transducers under test, and potentially by scattering around the body of the receiver (such as the recorder body). If the signal received at the measuring hydrophone does not reach steady-state conditions during the available echo-free time, it is not possible to observe the steady-state directly. This means that for a given tank size and transducer Q-factor, there will be a lower limiting frequency below which it is not possible to make measurements by conventional means.

To test the full free-field response of the recorders, free-field calibration methods must be established. It is possible that the recorder could be used as one of the three transducers in an implementation of three-transducer spherical-wave reciprocity calibration (with the recorder used as the receiver-only device, often labelled “H” in the procedures and standards) [5-7]. However, a more practical solution would be to undertake a comparison calibration with a calibrated reference hydrophone. At NPL, laboratory test tanks, and an open-water facility are available to support free-field recorder calibration. The latter is a fully instrumented floating laboratory situated on a freshwater reservoir (20 m depth) allowing free-field measurement to around 200 Hz. Both facilities use calibrated reference transmitters and hydrophones that can be used to test the system performance of autonomous recorders up to high kilohertz frequencies, and enable measurements to be made as a function of incidence angle (directional response measurements). By making multiple measurements with the recorder mounted in different orientations, it is possible to build up a picture of the three-dimensional directional response. This enables the effect of scattering from the recorder on the measured sound field to be quantified. For recorders where the hydrophone may be detached from the recorder body, the free-field calibration of the hydrophone may be undertaken independently using the methods described in international standards [5]. One additional difficulty for recorders with fixed hydrophones is that the wave interactions with the body will increase the time required for a steady-state response to be achieved (analogous to an increase the Q-factor of a hydrophone). This will increase the echo-free time required for calibration, which in turn will increase the free volume required in the calibration facility.

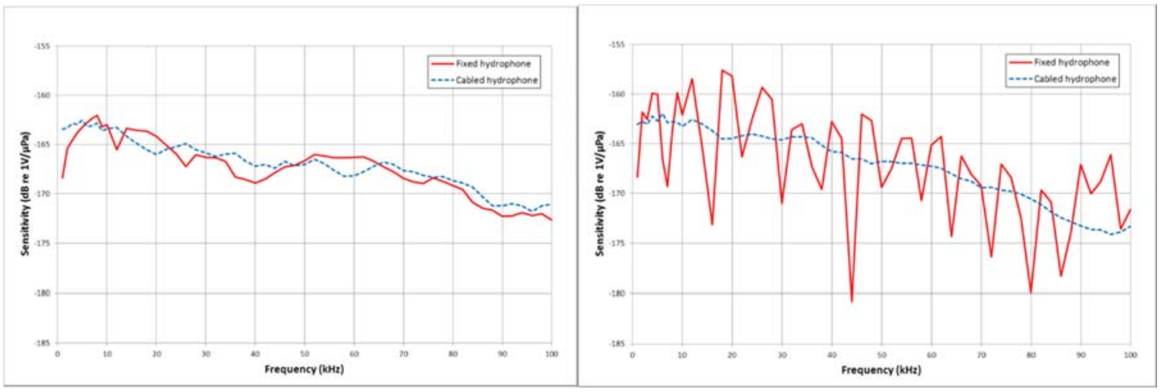

Fig 3. Comparison of frequency responses of a free-cabled hydrophone with a recorder with hydrophone fixed to the body in a direction side on to the body (upper plot) and end on to the body (lower plot).

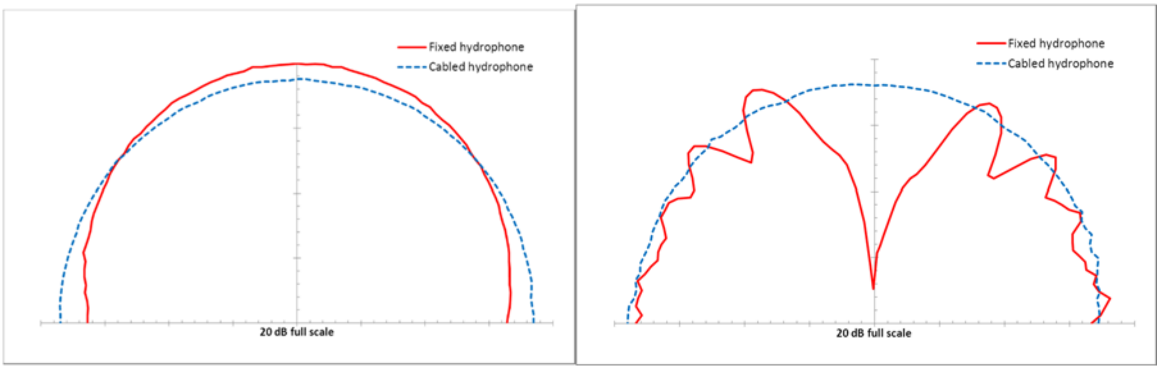

Fig. 4. Comparison of directional responses of recorder with hydrophone close to the recorder body and the same hydrophone on an extension cable at frequencies of 2 kHz (upper plot) and 44 kHz (lower plot).

It is desirable that the system sensitivity be invariant with frequency over the frequency range of interest (i.e. that it possess a “flat response”), to within an accepted tolerance. The flat system sensitivity of is important because the recorder needs to be able to record all the frequency components of interest in order to faithfully represent the acoustic signal. For a recorder with a hydrophone that is separately deployed from the recorder body, this requirement is not difficult to satisfy at frequencies up to tens of kilohertz. However, many of the commercially available devices consist of the hydrophone mounted either directly to the recorder body or close to it via a relatively short electrical cable. The recorder body is typically an air-filled cylinder that can scatter the acoustic signal and cause perturbation of the response at kilohertz frequencies. The combination of the direct and reflected waves causes interference, the nature of which will change depending on the frequency and the arrival angle for the sound wave. This can be a significant hindrance when the intention is to use the underwater autonomous recorder to measure sound from a particular direction. Similarly, if the hydrophone has a guard deployed around it (a protective cage to prevent damage of the element by impacts), this can influence the response at kilohertz frequencies. The combination of the direct and reflected waves causes interference, the nature of which will change depending on the acoustic frequency, thus causing fluctuations in the sensitivity with acoustic frequency (see Figure 3).

This problem is most acute for narrow-band signals received from a specific direction at kilohertz frequencies, where the fluctuation in sensitivity may be significant, and is less severe at frequencies below 1 kHz (though resonances in the body of the recorder may still have an influence). This is less of an issue for measurements of underwater sound in one third octave bands, where a degree of frequency averaging of the sensitivity will occur [3,4]. For the same reasons outlined above, the proximity of the recorder body can cause interference, which will change depending on the arrival angle for the sound wave. This can lead to significant perturbations to the directional response compared to that for the hydrophone alone. It has been shown that at kilohertz frequencies the recorder/hydrophone combination is not omnidirectional [3,4], and hence the sensitivity varies with angle of incidence, making the determination of the correct sensitivity challenging. Figure 4 illustrates the effect on a typical recorder geometry for hydrophone and recorder body. This problem is most acute for narrow-band signals received from a specific direction at kilohertz frequencies, where the fluctuation in sensitivity may be significant. At frequencies below 1 kHz, the effect is less severe, though there remains the possibility of an effect caused by resonances in the body of the recorder [16].

5. EMPIR PROJECT 15RPT02: "UNAC-LOW"

Work directly relevant to the calibration to marine acoustic recorders is being undertaken in a current European project (EMPIR PROJECT 15RPT02: "UNAC-LOW"). The goal of the project is to develop the European Metrological Capacity in underwater acoustic calibration for acoustic frequencies below 1 kHz by providing traceable measurement capabilities to meet the need for calibration of hydrophones and autonomous underwater acoustic noise recording systems. The project will develop the scientific and technical research capabilities in the field within Europe, and provide an improved metrology framework to underpin the absolute measurement of sound in the ocean in support of regulation and EU Directives, such as the Marine Strategy Framework Directive (MSFD) for which traceability is currently lacking. This project addresses the following scientific and technical objectives:

- To develop traceable measurement capabilities to meet the need for calibration of hydrophones at frequencies between 20 Hz and 1 kHz;
- To develop calibration methods and traceability for calibration of acoustic noise recorders and systems used for long-term ocean acoustic monitoring at frequencies between 20 Hz and 1 kHz;
- To develop strategies for long-term operation of the measurement capabilities including regulatory support, research collaborations, quality schemes and accreditation, contributing to development of a coherent metrology strategy for Europe within this field.

Partners in the project are Tubitak (Turkey), NPL (UK), DFM (Denmark), FOI (Sweden) and CNR-IDASC and ISPRA (Italy). The overall aim is improved traceability for hydrophone calibration which will provide manufacturers and users with vital confidence in measurement results. New methods for calibration of autonomous recorders will provide manufacturers with important feedback on key performance metrics for the first time, leading to development of improved system performance and validated calibration methods and better uncertainties. The new calibration guidance developed by the project will also be directly used by calibration laboratories, which will assure traceability of measurements performed by end users of recorder systems. More details about the project may be found on the project web-site: http://empir-unaclow.com/

6. ACKNOWLEDGMENT

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