Commercial Broad Range Calibration by Multi-Method Synthesis

Nicolas Wood[1], Emma Carline[2]

[1] Ocean Sonics, 110 Parkway Drive, Truro Heights, NS, Canada
[2] Ocean Sonics, 110 Parkway Drive, Truro Heights, NS, Canada

Nicolas Wood
Ocean Sonics
110 Parkway Drive
Truro Heights, B3L1N8
Canada
Nicolas.wood@oceansonics.com

Abstract: *There are a variety of challenges that come with calibrating hydrophones. One of those is that it is not possible to calibrate their full frequency range using a single test fixture. In-tank calibrations can be done down to the low-kHz range (tank size permitting) but there are many applications for which there are still several decades of frequency range of interest below that point. Open water calibrations can be done for broader frequency ranges but cost limits their application in a commercial environment. This paper will discuss experimentation with combining additional lab-based calibration methods to produce a synthesized calibration ranging from 1 Hz up to 200 kHz in a production setting. The work done compares tank-based calibrations by comparison and low frequency pistonphone measurements to comparison calibrations done using a vibrating water column apparatus. Coiled waveguides were tested previously, thought reliable results were not achieved. Favourable results were produced in terms of achieving good agreement between the calibration fixtures in their respective frequency ranges.. The vibrating water column fixture worked in a limited range though an improved fixture may permit increased useable frequency range.*

Keywords: *Calibration, Low frequency*

1. INTRODUCTION

Ocean Sonics designs and builds the icListen, a broadband digital ethernet-based hydrophone with edge computing capabilities. Accurate estimates of the hydrophone's sensitivity are essential both in-house for quality control and for the end user. The calibration certificate provides the hydrophone sensitivity at select frequencies across the frequency range of the hydrophone. There are some limitations with the current calibration method however, with regards to the range of frequencies that can be calibrated.

The current calibrations use a tank-based method of calibration by comparison. A hydrophone unit under test (UUT) is compared with a reference unit with known sensitivity. An uncalibrated projector, the Ocean Sonics-made icTalk, is placed in the centre of the tank with the two hydrophones equally spaced on either side of the projector. The projector plays a sequence of short-duration tones at a series of frequencies between 10 and 200 kHz for icListen HF hydrophones and between 5 and 12.5 kHz for the icListen AF hydrophones. The layout for tank calibrations is shown in Figure 1.

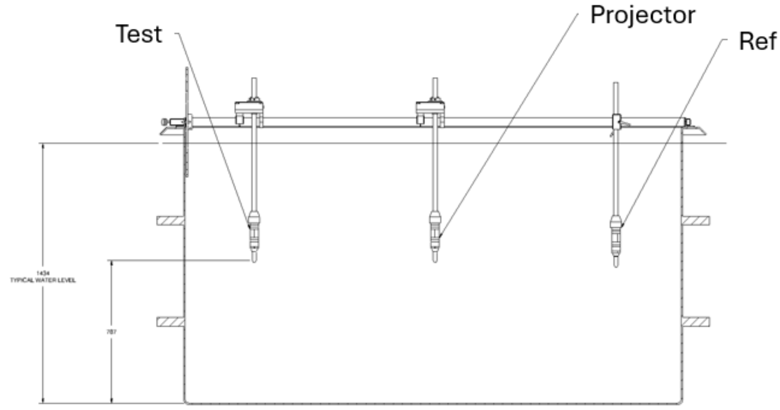

Figure 1: Calibration tank layout with Test and Reference hydrophones and icTalk projector.

To calculate the Receive Voltage Sensitivity (RVS) of the UUT, we assume that the sound pressures measured at the UUT and the reference unit are the same. Therefore, we get the following equality:

$$RVS_{UUT}(f) = RVS_{REF}(f) - V_{REF}(f) + V_{UUT}(f) \quad (1)$$

Where $V_{REF}(f)$ is rhe received voltage level at the reference hydrophone at frequency f in dBV, $RVS_{REF}(f)$ is the sensitivity in dBV/µPa for the reference unit at frequency f, and $V_{UUT}(f)$ and $RVS_{UUT}(f)$ are the corresponding quantities for the UUT.

The goal of the calibration is to calculate $RVS_{UUT}(f)$ for all frequencies f in the range of target frequencies. The calculation is straightforward, but the challenge is obtaining an accurate estimate of $V_{REF}(f)$ and $V_{UUT}(f)$ through in-tank measurements. The standard range calibrations at Ocean Sonics as mentioned previously follow the guidelines provided in the IEC 60565 standard [1] and can measure these parameters to a satisfactory level of precision.

In-tank calibrations are limited in useful frequency range by the tank dimensions. This is due to requirements on the data window. According to the IEC60565 standard, the data window should generally include at least one full period of the waveform in the steady-state period of the waveform while excluding the portion of the signal containing reflections from the tank surfaces. The Ocean Sonics calibration tank is 2.74m long, 1.52

m wide, and the water depth is typically 1.41 m. The hydrophones are each spaced 1.00 m from the projector and typically 0.81 m deep. Therefore, when the projector emits a tone, the time between the first arrival and the arrival of the first reflection is 380 µs. However, the first part of the signal contains the transient so the minimum frequency that can be measured while meeting the data window requirements is approximately 4 kHz. While a standard pistonphone can provide a point at 250 Hz or similar, there is a desire to calibrate across the full lower frequency range.

Effective low frequency calibration methods exist but we have the additional practical requirements that the calibration methods use our own equipment to facilitate timing precision with the test hydrophones and that they permit frequent calibrations with good ease of use. Open water techniques or the laser pistonphone method and coupler reciprocity method described in [2] are not appropriate for the above reasons.

A method using a novel coil-waveguide method was previously investigated for low frequency calibrations at Ocean Sonics [3] with a reasonable form factor of the coil-shaped wave guide. In principle the calibrator worked but it was not possible to perform calibrations with the precision of the in-tank calibrations.

The primary objective of the work at hand was to investigate additional calibration methods to expand the frequency range of Ocean Sonics calibrations. When selecting low frequency calibration methods, consideration was given to the ease of use of moving a UUT hydrophone between calibration fixtures and the ability to use the same icTalk projector electronics for the excitation signals. Using the icTalk enables easy timing synchronization with the hydrophones and maintains the same methods of programmatic control of all the devices in the different calibration techniques.

Two methods were considered that complied with these requirements: a vibrating column test fixture and a modification of the in-tank method to allow lower frequencies. Together it was hypothesized that these methods could extend calibrations from a minimum of 5 kHz, down to 1 Hz.

A vibrating column calibration fixture uses a vertically moving container to vary the pressure experienced by the UUT. This can be done with a physics-based approach with an actuator with positional feedback with pressure levels calculated from the actuator displacement, or with the use of a reference hydrophone.

For the modifications to the in-tank measurements, two approaches were considered which are essentially relaxations of the data window requirements.

The first modification was to reduce the size of the data window, allowing partial periods of the waveforms. In calculating the rms of the received voltage, the current method repeats each tone frequency twice where the second tone is 90-degree phase shifted. The signals are then squared and point-wise summed, giving a DC-signal with amplitude equal to that of the tones. This is possible due to the identity $cos^2(\theta) + sin^2(\theta) = 1$. In theory, this should give the same amplitude even if the data window length is substantially less than a full period.

The second modification was to allow the sampling window to extend into the reflection period of the signal. While at first this appears ill-advised, there are a couple of reasons that this may be viable for low frequency tones in our setup. The first of these is that for high frequencies the reflections can appear highly random which is likely due to small (mm range) variations in hydrophone or projector positioning equating to large variations in the phase difference of the reflected signals. However, for very low frequencies the relative phase shift between the two positions in the tank is very small so the received reflections interfere with the generated waveform in near-identical manners. This was already observed in previous tests. A remaining issue was the presence of phase inversions due to reflections as well as stepwise transients that are present at the beginning and end of the windowed drive signal. The proposed solution was to apply heavy bandpass filtering. While this greatly modifies the signal amplitude, the fact that the UUT signal is a scalar multiple of the reference signal suggests that filtering would preserve this relationship and the sensitivity calculation in equation (1) would still hold. It seemed that it would be at least worth trying the method since it is easy to do with our current tank setup.

2. METHODS

The two calibration methods were tested and evaluated at the Ocean Sonics facility in Truro Heights, Nova Scotia.

Vibrating Column Test Fixture

A vibrating column calibration fixture was designed and built using readily available components. Due to the requirement to follow a similar procedure to the in-tank calibrations, the calibration fixture was designed to use a second reference hydrophone. A voice coil motor (VCM) was used to drive the bottom of the container. The VCM was able to be driven from a modified icTalk boardset which meant that interfacing with the calibration fixture was unchanged from the in-tank calibrations. The vibrating column tests were done with a steady state 5 second tone at each frequency step.

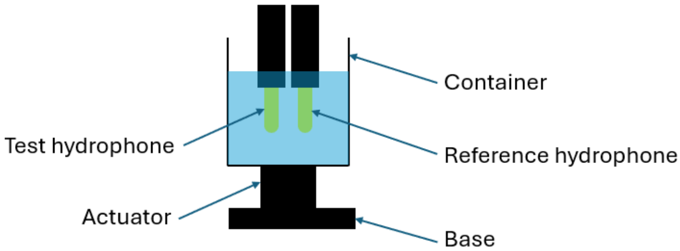

Figure 2: Vibrating column test fixture using a reference hydrophone and no positional feedback.

Initial tests were conducted to first confirm that the test fixture could produce acceptable sound levels at the frequency ranges of interest. Recordings of steady-state tones were made and a processing script was designed to calculate the recorded signal amplitudes. The calibration fixture was tested in the frequency range of 5 Hz to 200 Hz.

The hydrophone mount was designed to enable modification of the hydrophone position within the container to allow testing for any variation of signal intensity with the hydrophone position.

In-Tank Calibration Processing Modifications

To test the modifications of the in-tank calibration, the standard icTalk projector was replaced by the LF icTalk, which used a modified driver and low frequency transducer. This was necessary as the standard icTalk has a lower frequency limit of approximately 4 kHz. It was found that the LF icTalk did not produce clean tones; they seem to be contaminated with high frequency signals, possibly an issue with the amplifier. However, despite this, by filtering and comparing results with a standard icTalk calibration it was found that the sensitivity measurements were not greatly affected. For example, at 10 kHz, the LF icTalk-measured sensitivity was found to be -178.0 ± 0.1 dB re 1 V/uPA, over 4 different runs. The standard calibration gave a value of -178.0 dB V re 1 uPa. The filter used was a 4-pole Butterworth bandpass filter with lower cut-off at 75% of the tone frequency and upper cut-off at 125% of the frequency. The filter was applied forward and then backward to preserve phase. Filtering heavily modified the waveform, and the effect of doing of this should be studied more in the future.

To evaluate the in-tank calibration modifications, we first looked at the effect of shortening the data window. For a valid test, we tested tone frequencies where the true sensitivity could be measured using the standard approach, i.e., there was more than one cycle of the tone available before the arrival of the first reflection. Tone frequencies of 5.1, 5.4, 5.7, and 6 kHz were selected for testing since these are near the bottom of the current in-tank calibration frequency range. For the test, the data window was progressively shortened, from 1 full cycle to an extreme 5% of a cycle. The idea was that if the sensitivity did not change much for the 6 kHz tone despite using a short data window, then the same should be true for lower frequency tones, validating the use of partial cycle data windows for low frequency calibrations.

Secondly, we looked at the effect of allowing the portion of the signal that contains reflections to be included in the data window. Again, the testing was conducted for tones with frequencies of 5.1, 5.4, 5.7, and 6 kHz. The data window length was fixed at 1 cycle and progressively shifted to the right by 31 µs to capture more and more of the reflection-containing part of the signal.

Finally, we tested the in-tank method modifications for frequencies between 200 Hz and 6 kHz, collecting data over multiple runs. For each tone frequency, the data window length varied and sometimes included reflections. Though the true sensitivity in this frequency range was not known, we wanted to see how much variability there was between runs. If there was a large difference in the sensitivity estimates between runs, that suggests that the method has poor repeatability and would be unsuitable for Ocean Sonics calibrations.

It should be noted that the reference hydrophone unit was calibrated by NPL down to 2 kHz, with measurements at points spaced by 500 Hz between 2 and 10 kHz. Below that, the sensitivity of the reference unit was estimated by interpolating between the pistonphone measurement at 250 Hz and the NPL value at 2 kHz. We recognize that this introduces some uncertainty in the sensitivity estimates of the UUT.

3. RESULTS

Vibrating Column Test Fixture Results

The vibrating column test fixture had some unexpected challenges, the main one being that the frequency range was limited more than was hoped by what appeared to be mechanical modes in the container in the 60-200 Hz range. This limited the useful calibration range to 1-55 Hz. The 60 Hz noise may have also been from mains interference but the higher frequency interference seemed likely to be a result of mechanical modes, which was roughly validated by a low-fidelity FEA model. This is visible in Figure 3 where the frequency responses become erratic in the upper portion of the frequency band. Even in the flat section there is more variation than would be desired on a run-to-run basis. However it should be noted that the average of a number of runs follows the expected curve to within 0.5 dB so while the precision was an issue, the actual calibrated values were correct.

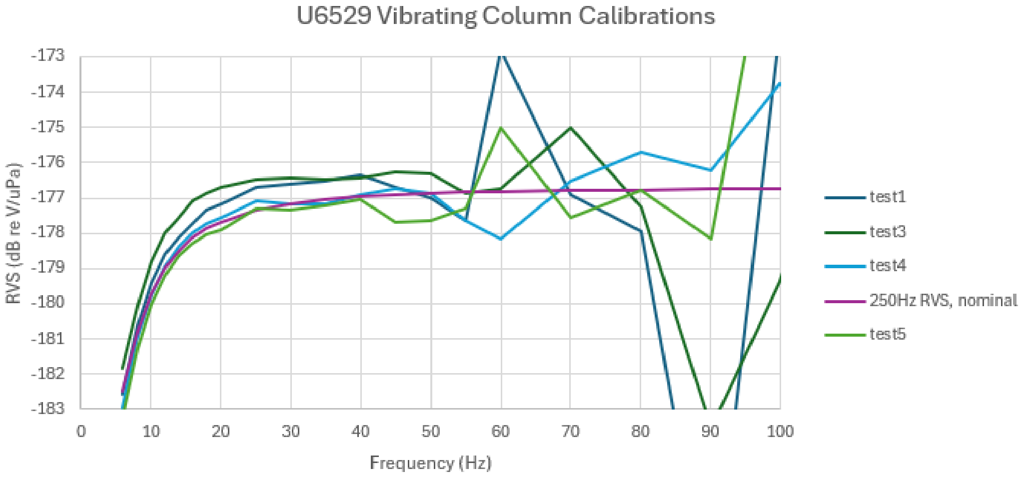

Figure 3: Calibration results in the vibrating column test fixture.

The investigation into the effect of the hydrophone positioning revealed inconsistency in the sound levels when the hydrophone position was modified laterally across with width of the container. This is shown in Figure 4 where the sound level as a function of hydrophone position is shown for a series of frequencies across two tests.

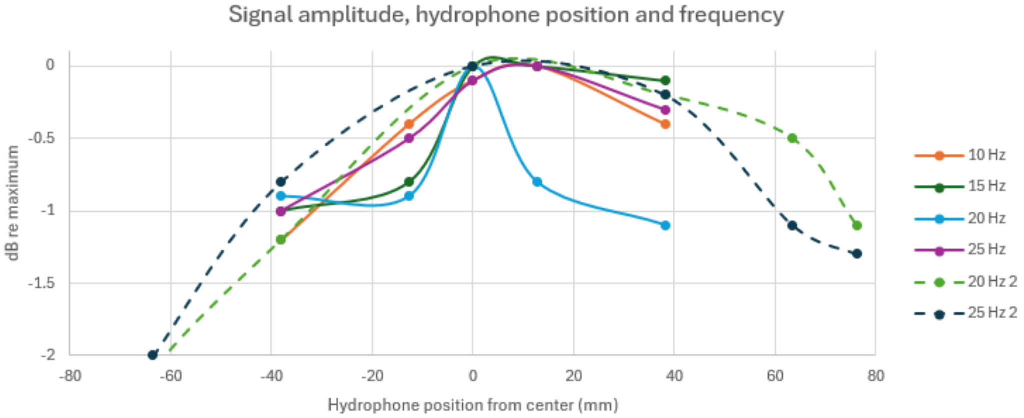

Figure 4: Measured sound level with lateral position inside vibrating column test fixture.

The results are consistent in that the highest sound levels were at the centre of the container but there was some further inconsistency between measurements that would not be acceptable in a calibration. The hydrophone sensor tips were placed at a spacing of 50mm so it appeared that amplitude errors of 0.5-1.0 dB could readily occur even if assuming good repeatability of the hydrophone positioning.

Overall, the vibrating column test fixture achieved some level of its objective of showing that very low frequency calibrations may be possible without significant changes to the existing calibration processes used with the in-tank calibrations. Though it was clear that further work would be needed on the specifics of the design, with a focus on the use of a more rigid container.

In-Tank Calibration Processing Modifications Results

Results for the in-tank calibration modification tests are shown in Figures 5 – 8.

Figure 5 shows an example of a 6 kHz tone with the data window used for processing highlighted by a red box. The original waveform (orange curve) is visibly very messy, as noted in the previous section, which is a known issue with the LF icTalk with short duration tones. The filtered waveform (blue curve) is very different from the original, however, agrees relatively well in the data window. The reference and UUT waveforms do agree (i.e. are scalar multiples of each other) up until the end of the data window, which is a critical assumption of the sensitivity calculation.

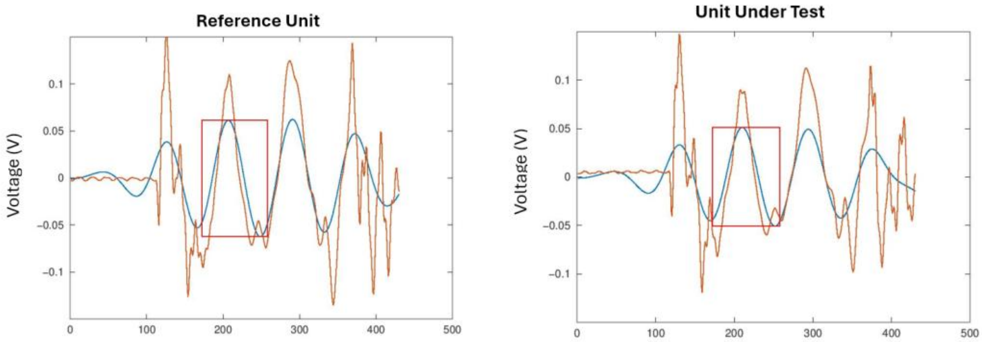

Figure 5. Example of data window (red) overlaid on filtered signal (blue) and original waveform (orange), Top: Reference unit, Bottom: Unit Under Test (UUT).

Reducing the data window length even down to an unreasonable 0.05 cycles did not have a large effect on the sensitivity calculation, as shown in Figure 6. The difference in sensitivity over all data window lengths tested was less than 0.2 dB re 1 V/uPa.

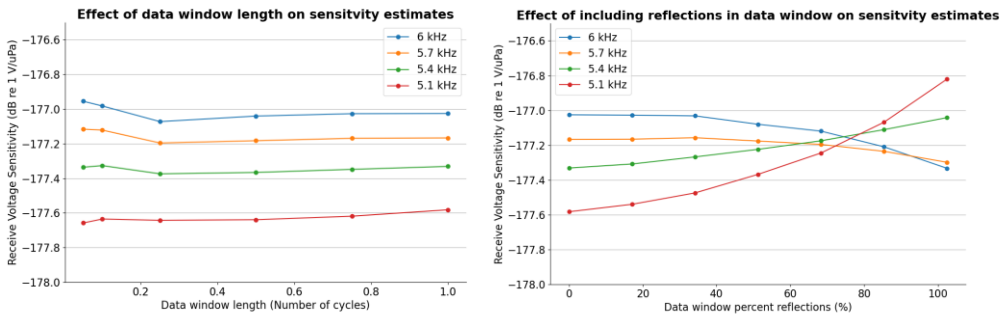

Figure 6. Left - Effect of using a data window of length less than one tone period on hydrophone sensitivity estimate. Right - Effect of including reflection-containing portion of the signal in the data window.

Allowing reflections in the data window had a greater effect on the sensitivity estimates than shortening the data window, which can be seen also in Figure 6. The changes in sensitivity were frequency dependent. However, what was consistent was that the sensitivity estimates diverged further from the original non-reflections estimate as more of the reflecting-containing portion of the signal was included. Interestingly, for all frequencies tested, the difference between the 0% reflections data window and the 100% reflections data window was less than 1 dB re 1 V/uPa. In particular, the difference between 0% and 40% reflections was under 0.2 dB re 1 V/uPa.

Figure 8 shows a subet of the low frequency calibrations performed using the in-tank calibration modifications. Below 3 kHz and above 500 Hz, the sensitivity estimates vary by up to +/- 1 dB re 1 V/uPa, however there were a variety of parameters being tested including tone intervals and processing parameters, so this variation does not represent the repeatability using a consistent testing protocol. Below 400 Hz, the results were erratic.

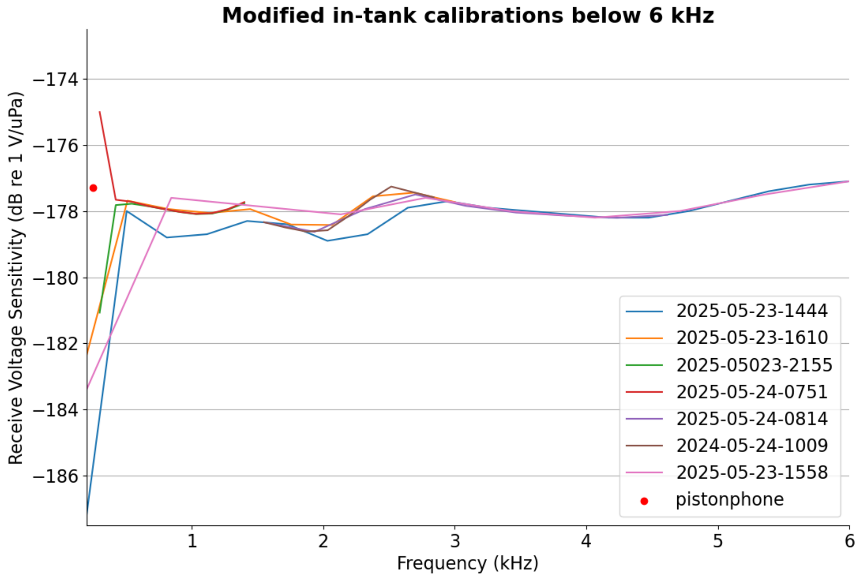

Figure 7. Multiple calibrations using modified in-tank method. The pistonphone measurement at 250 Hz is shown for reference.

Figure 8 provides a combined calibration curve for hydrophone S/N 2080 synthesized from a standard in-tank high frequency calibration, an in-tank low frequency calibration as described here, a GRAS 42AG calibrator measurement (250 Hz), and a vibrating column measurement. Overall, the agreement between the methods seems fairly good.

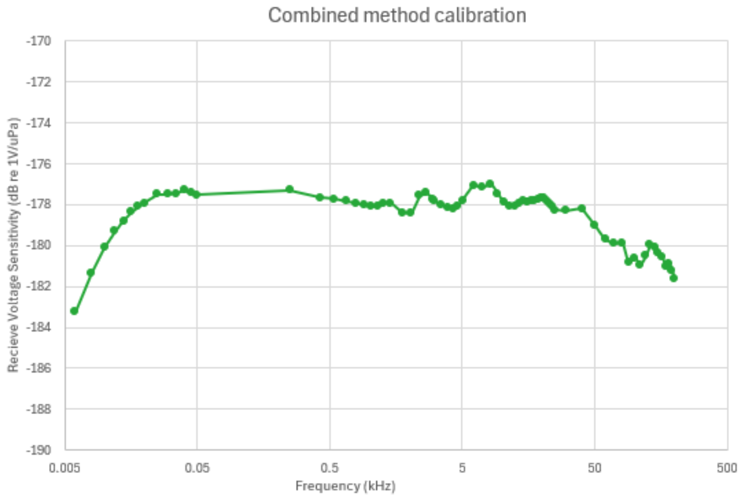

Figure 8: Combined calibration curve for hydrophone S/N 2080.

4. DISCUSSION

This paper outlines preliminary efforts to perform full-bandwidth calibrations choosing specifically techniques that can be performed using the icListen hydrophone and icTalk projector. The techniques used were selected to minimize the amount of effort to integrate multiple calibration methods into a single system. Two methods were used to extend the functional calibration minimum frequency from 4 kHz to 5 Hz. The synthesized calibration shown in Figure 8 suggests that the methods outlined here may be viable for this purpose however additional work will have to be done to further validate both methods and improve upon the design of the vibrating column fixture used here. Ideally there would be overlap between each method, but it should be possible to extend the frequency range of the vibrating column to reach the 500 Hz or more. If further testing instead shows that this is not possible then there are other calibration methods that have been shown to work in the single Hz to 100's of Hz range that could be implemented. Regarding the sampling of data beyond the reflection-free period, there are trade-offs between the window length and calibration precision. Further work is needed to determine if it can be beneficial. Using a small percentages of a single wave period appears to have the potential to provide meaningful results when using averaged signals with a 90° offset. Even without extending into the reflection period, small cycle percentages could potentially reach 500 Hz.

REFERENCES

[1] **BSI 2007**. IEC 60556:2007 – Underwater acoustics – Hydrophones – Calibration in the frequency range 0,01 Hz to 1 MHz. International Electrotechnical Commission.

[2] **Metrology for low frequency sound and vibration.** https://www.ptb.de/empir2020/infra-auv/information-communication/publications/good-practice-guide/part-3-hydroacoustic-technology/developments-in-primary-calibration/ (Accessed: 25 May 2025)

[3] Drinnan, R. (2023). Low-Frequency Hydrophone Calibration Using Elastic Waveguides [Dalhousie University]. Dalhousie University Library: https://dalspace.library.dal.ca/items/6c0cc4be-7adf-4d11-9fa3-8b5eee638434