DESIGNING PRACTICAL ON-SITE CALIBRATION PROTOCOLS FOR ACOUSTIC SYSTEMS: KEY ELEMENTS AND PITFALLS

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Abstract: *Although acoustic systems are increasingly being used for environmental and noise surveys of marine energy devices, there are currently no standard protocols for the on-site full bandwidth calibration of these systems. Reports often include little or no information on the methods of calibration used before, during or after surveys. Without proper calibration, the sound levels may be far from accurate, leading to skewed reporting and inaccurate conclusions.*

Hydrophone calibrations from internationally recognised standardisation centres, such as NPL, allow providers to reference their systems to international standards. Marine renewable energy devices, however, are often deployed in remote areas and it is not always practical or cost-effective to send every acoustic system to be independently tested before every deployment. On-site referencing of multiple units to a single standardised system can help improve calibration traceability. Although this may at first appear relatively simple, the production of an accurate, full-spectrum calibration, particularly in real-world test sites, is surprisingly difficult.

Keywords: *Calibration, Marine Energy, Standards, Reporting*

1. INTRODUCTION

Calibration of acoustic systems can seem complex and is particularly difficult to achieve in remote areas, away from services for standard referencing of equipment. This is true for acoustic surveys of marine energy devices, which are often deployed on remote areas of coast. Setting up a portable calibration system can avoid these difficulties.

This paper will describe the key elements involved and pitfalls to avoid when setting up such a system. It will use work at the European Marine Energy Centre as an example, with particular reference to the whole system comparison calibration of Drifting Acoustic Recorder and Tracker (DART) units.

2. KEY ELEMENTS

The main focus for ensuring accurate calibrations should be to assess and reduce levels of uncertainty throughout the calibration system. Standards organisations have created guidance for both calibration techniques and the assessment of uncertainty. These provide extensive information to ensure accurate characterisation of acoustic systems in laboratory conditions, including good practice and pitfalls to avoid. It is recommended that these are consulted during detailed design of calibrations [1, 2, 3, 4].

For simplicity, these descriptions of uncertainty are typically grouped into type A and type B uncertainties. Type A are ‘random’ uncertainties; those which can be calculated through repeated measurement. Type B are ‘systematic’ uncertainties, which can be predicted and reduced through thoughtful calibration design.

This section will provide a brief overview of important considerations for initial calibration design. This will use as an example the comparison calibration design for the DART units, shown in Figure 1.

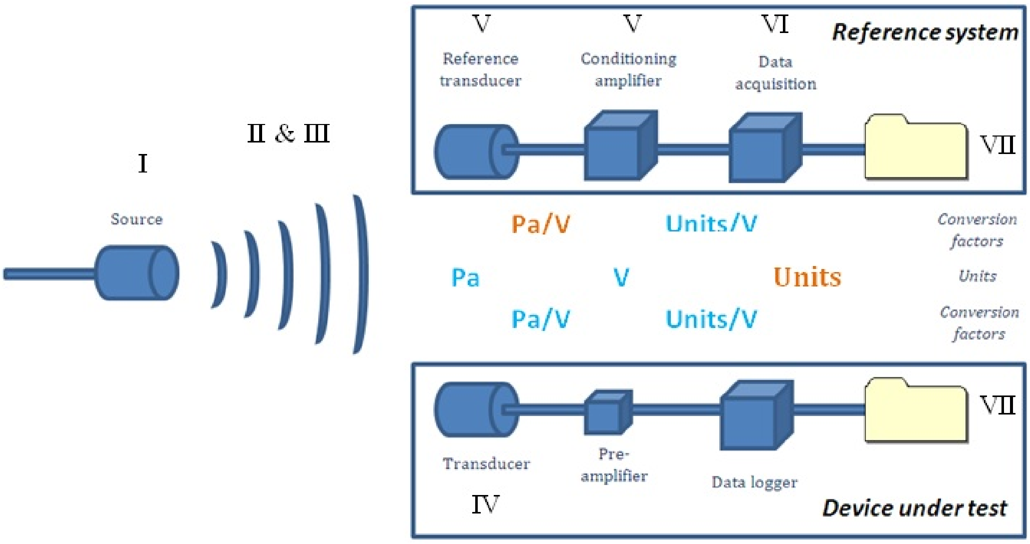

*Figure 1: Overview of DARTs comparison calibration, including known data (**Orange**) from referenced data (Pa/V) and acquired data (units), and unknown physical quantities and conversion factors (**Blue**) that require further measurement. Elements of the system (I-VII) are described in Table 1.*

Whole system comparison calibration

Comparison calibration is relatively simple and fast, but requires a large body of water and a stable, calibrated reference hydrophone (see section 3 for details). These requirements can usually be achieved in remote marine areas, through access to the sea and annual reference calibrations. More information on alternative calibration techniques can be found in ISO standards and guidance literature [2].

The technique uses a source, emitting hydrophone and two receiving systems. The first receiver, the *reference system,* consists of a hydrophone and subsequent signal conditioning pre-calibrated to international standards to provide pressure in Pascals (Pa) from measured voltages, or **Pa/V**.
The reference hydrophone is then placed next to a hydrophone from a second *un-calibrated system*, for which only **Unit** values (such as bits in a .wav file) are known.
If both hydrophones are located at the same distance from the source, then the acoustic pressure (in Pa) at both hydrophones should be the same. It is therefore possible to use the Pa excitement of the reference system to calculate Pa/Unit values for the un-calibrated system.

However, there are a number of unknowns; for example, how is the voltage from the reference hydrophone converted to units? Typically this will involve the analog-to-digital converter (ADC) within a data acquisition unit. Thus the conversion factor of the ADC, the Units/V produced, will need to be estimated before Pa values can be calculated from measurements by the reference system.
The conversion factors and physical quantities highlighted in blue in Figure 1 are all unknown; by using additional measurements (see section 3), it is possible to calculate conversion factors, which will then provide a basis for calculating the physical quantities.

Estimating uncertainty

Uncertainty in measurement of any part of the process, including the measurement of conversion factors, could affect the accuracy of the whole calibration. Therefore, it is important to predict and test those elements that could create uncertainty. Table 1 outlines the expected uncertainties for each aspect of the DART's calibration, as further discussed in section 3.
As previously described, type A uncertainties are reduced through repeated measurements, whilst type B are typically reduced by modifying the system design. Often systematic uncertainties will not become obvious until the calibration is trialled, so it is useful to plan test calibrations well in advance of data gathering, in order to allow time for purchasing and testing any additional equipment if required.

When estimating uncertainty, it is important to convert all estimates and measurements to the same units. This can be simplest to achieve using percentages of uncertainty values. It is also useful to note that logarithmic units may make certain calculations more difficult; thus it may be helpful to work with linear units.

Uncertainty	Type A (random)	Type B (Systematic)	Mitigation	Detail of action taken
I. Signal generation		Waveform shape and levels may change	B -Test signals and make waveforms as similar as possible	B - Signals tested Hardware problems causing irregularities in waveforms generated at certain frequencies (e.g. 10kHz) – new hardware bought.
II. Signal transmission	Random changes due to water movement, debris, etc.	Reflections, mounting vibrations, bubbles, other problems with set-up	A – repeat B – Avoid reflections/rig vibrations/Bubbles	A – 30 repeats for each frequency calibration, 3 repeats of each set-up. B – Deep channel chosen and reflections calculated. Vibration isolation & bubble removal to be included.
III. Electrical/ acoustic noise	Random electrical/ acoustic noise	Equipment noise, noisy test area	A – repeat B – Reduce equipment noise to minimum/Avoid noisy areas	A – Repeats, as above. B – Low noise calibration equipment used. New DAQ hardware to be included. Avoiding times of environmental/anthropogenic noise at test site.
IV. Device under test receiving (Pa-unit)	Random changes in Acoustic response	Pa-unit transduction will not be linear & may change over time	B - repeated calibration of the whole system	A – 3 repeats of calibration (short-term) and repeats before, during and after surveys. B – Calibration of frequency response. Amplitude response to be included.
V. Reference equipment receiving (Pa-V)	Random changes in Acoustic response	May not be calibrated accurately & Pa-V transduction may change over time	B - Re-calibrate often and track change	A&B - Reference hydrophone and conditioner calibrated. To be recalibrated again asap.
VI. ADC accuracy (V-Unit)	Random changes in electrical response	V-unit conversion will not be linear & may change over time	A - repeated calibration B –calibration of DAQ	A – DAQ output/input calibrated 5 times using a multimeter/calibrated output. B - Calibration of frequency and amplitude response. More accurate electronic testing equipment could be used in future iterations.
VII. Analysis accuracy		Different methods of analysis will create different results for the same analysis (e.g. fft)	B -Compare and decide upon most accurate method	B – Taking into account the transmission environment and sample rate of the devices under test (DARTs), a half pulse Fourier transform was used for amplitude, with frequency bins of 512 providing the best compromise of sharp, but inclusive peaks.

Table 1: Example of a simple uncertainty analysis, taking into account expected sources of uncertainty. Detail includes actions that were successfully used to reduce uncertainty (Orange) and actions needed to further reduce uncertainty (Blue).

3. POTENTIAL PITFALLS

Signal generation and acquisition

The first potential pitfall for a calibration is the calibration tone; both the generation of the electrical signal and the transduction into a physical signal can produce frequency and amplitude artefacts. Therefore, it is important to check the calibration signal and modify the calibration system as necessary. For example, in Table 1, a system with better defined waveforms was required; therefore equipment with improved specifications was purchased. Ideally, the source hydrophone should also be calibrated across the frequency range of interest in order to reduce uncertainties in source amplitude.

Generation and acquisition systems also need to be designed to cover all frequencies required for acoustic surveys. For example, if surveys require measurement up to a frequency of 200 kHz then it will be necessary to use a generation and acquisition system capable of working at these frequencies, i.e. an acquisition system with a sample rate of at least 400 kHz.

Signal transmission

A major influence upon the transmission of the signal is the environment. Uncertainty due to random changes can be reduced using multiple repeats at each frequency. However, systemic effects, such as the effect of boundaries in the test area, must be designed into the calibration. For example, hydrophones must be placed at a depth such that reflections from the surface and bottom reach the receiving hydrophones a certain period after the direct signal. In Table 1 (VII), the calibration pulse is analysed using a 512 Fourier transform, thus a period of at least 512 samples will be needed before the first reflection is received.

The time between direct and reflected signals is related to the distance between the source and receiving hydrophones, since a shorter distance will provide more time before reflections are received. However, this will increase the minimum frequency available for testing. This frequency can be calculated, based upon estimates of the 'far-field' [2], using:

$$MinFreq = 2 \times \left(\frac{c}{distance}\right) \tag{10}$$

with distance in meters and c as speed of sound (in m/s) within the local environment.

It is therefore important to realise that the typical minimum frequency for a comparison calibration will be low kHz and other methods must be used for calibrating low frequencies, such as a pistonphone calibration [2]. It may be necessary to reduce hydrophone distance, and so increase the minimum frequency, in shallow test areas.

Speed of sound itself can be calculated using CTD measurements of the calibration site. Guidance on the measurement and calculation of speed of sound can be found on the NPL website [5].

Finally, the positioning, mounting and wetting of the hydrophones can influence transmission. Inaccurate positioning can change the amplitude of signals, whilst mounts can create vibrational artefacts. Therefore it is important to state and check the hydrophone distances and use guidance to avoid mount vibrations and air bubbles [6, 7].

Additional measurements

Additional measurements, such as CTD measurements, will also require calculation of uncertainty, typically through calibration techniques or using standardised calibrated equipment. The importance of these calibrations will depend upon the probable effect on calibration; for example, inaccurate reference hydrophone calibration or data acquisition equipement response calibration could greatly affect values, whereas inaccurate CTD measurements may not have a great effect.

Equipment accuracy

The accuracy of acquisition equipment and the equipment used to test this equipment must be checked over time and if calibration methods change. For example, data acquisition equipment can be tested with voltage signals calibrated using multi-meter measurements. Systematic uncertainties of electrical equipment can be avoided through regular testing and comparison of voltage and unit values; for example, hydrophone connections may produce different values if connected before or after powering elements of the system.

Calculation of values

It is useful to check all calculations performed on measurements manually before any automation is introduced into the calibration process. There are a number of steps required for calibrations and it is essential to ensure that each step is calculated correctly. This is particularly important when using analysis packages to calculate the amplitude of received pulses since the values can change depending upon the section of pulse analysed and the length of section analysed. Ideally, the section analysed should be as long as possible, although this may not be feasible in practice.

Finally, it is good practice to perform these calculations in SI units before converting to dB; as previously mentioned use of logarithmic units can complicate certain calculations. It is also good practice to use RMS amplitudes and clarify this use in reports; this avoids comparison of peak and RMS amplitude values, which, although proportional, are not equivalent.

4. CALCULATING UNCERTAINTY

The method for calculating uncertainties differs for each type of uncertainty. In addition, the following methods assume that elements are independent of each other, whereas correlated elements require additional calculation [3].

Calculating type A uncertainties

These uncertainties are estimated through the calculation of arithmetic mean and standard deviation of repeated measurements. Guidelines recommend between 4-10 repetitions to cover most measurements, although accuracy can be slightly improved with additional repeats [1].

Arithmetic mean ($\overline{\chi}$) is simply calculated using:

$$\overline{\chi} = \frac{\sum \chi_i}{n} \tag{1}$$

where n is the number of repeats, and $\sum \chi_i$ is the sum of their values.
Standard deviation (σ) is then calculated using:

$$\sigma = \frac{\sum (\chi_i - \overline{\chi})}{n-1} \tag{2}$$

Percentage standard deviation can then be calculated:

$$\sigma(\%) = \frac{\sigma}{\overline{\chi}} \tag{3}$$

Finally standard type A uncertainty (u_a) is calculated using:

$$u_a = \frac{\sigma(\%)}{\sqrt{n}} \tag{4}$$

Calculating type B uncertainties

Type B uncertainties are estimated using the best information available and experience of the systems being calibrated. In practice, an estimate is made of the upper and lower bounds of expected error, the difference between these values taken and divided by 2:

$$a = \frac{(upper - lower)}{2} \tag{5}$$

The mean is typically half-way between these two values:

$$\overline{\chi} = lower + a \tag{6}$$

Standard uncertainty can then be calculated based upon the expected distribution of the error. For example, if all values across the range from the upper to lower estimate are expected to be equally probable, then a rectangular distribution can be used:

$$u_b = \frac{a}{\sqrt{3}} \tag{7}$$

whilst errors expected to cluster around mean, i.e. in a bell-shape, can be calculated using:

$$u_b = 1.48a \tag{8}$$

Finally, the percentage uncertainty can be calculated as above.

Calculating combined uncertainties

Once the uncertainty for each element has been calculated, it is possible to calculate the combined uncertainties, u_c, through the formula:

$$u_c = \sqrt{(u_1 + u_2 + u_3 + ...} \tag{9}$$

This formula is useable for uncertainties that combine linearly to produce a total uncertainty. This is not generally the case for calibrations, since each uncertainty is typically independent of others, but it can provide a simple 'worse-case scenario' estimate.

Additional, more complicated, means to calculate combined uncertainty are detailed in international standards for uncertainty and measurement [3].

5. ACKNOWLEGEMENTS

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