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Calibration Methods for Vector Sensors

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Abstract

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Chapter 1

Introduction

Any measurement equipment should be capable of providing accurate data. That accuracy is guaranteed by the periodic proper calibration of the equipment according to a specific technical standard. Underwater acoustic measurement devices are no exception and several standards are defined for hydrophone calibration by international institutions, such as:

- IEC 60500:2017 - Underwater acoustics - Hydrophones - Properties of hydrophones in the frequency range 1 Hz to 500 kHz
- IEC 60565-1:2020 - Underwater acoustics - Hydrophones - Part 1: Procedures for free field calibration of hydrophones
- IEC 60565-2:2019 - Underwater acoustics - Hydrophones - Calibration of hydrophones - Part 2: Procedures for low frequency pressure calibration
- ANSI/ASA S1.20:2012 - Procedures for Calibration of Underwater Electroacoustic Transducers, New York: American National Standards Institute

These standards define how the calibration methods work and how the measurement should be performed. This calibration consists mainly in the determination of the transducer response as a function of frequency and direction, as well as the device sensitivity. Additional calibration may be done to determine electrical properties, measure stability (when changing environmental parameters, such as temperature) or find device dynamic range. These methods are well established over the years, however, they were developed for hydrophones. More recently some new technologies have emerged, such as vector sensors or autonomous recorders, that opened new doors in underwater monitoring.

Vector sensors are devices capable of measure particle motion and pressure, allowing to determine the propagation direction of an acoustic wave. However, vector sensors don't have any standard calibration methodology, even if in some literature it is suggested to use the same methodologies as those used for hydrophones [1]. The basic assumption is that a vector sensor can measure the sound pressure, so the same methodologies should be used. In fact, a traditional approach to create a vector sensor is to use an hydrophone array, containing several identical hydrophones with a known distance between them.

The calibration methods for hydrophone based vector sensors attempt to determine its free field pressure sensitivity using either the free field reciprocity method or the comparison method, in the same facilities that can be used for hydrophone calibration. Free field sensitivity means that no reflections from the boundaries should occur, even if this is extremely difficult to avoid in practice. An approximation is done by removing the reflections of the received signal using a time gated window or by using signal processing techniques.

If a vector sensor uses accelerometers, it is possible to calibrate these devices through the standard for vibration sensors calibrations (ISO 16063). This standard is also well defined and cover several methods, being the most common and easy to use the comparison method (defined in part 21 of the standard description). It relies on the use of a shaker, comparing the device to calibrate with a reference device. These methods don't include loading and coupling aspects of water, even if they are relatively easy to perform. Also, the structure where the accelerometers are mounted will have natural resonances and will contribute to the system response which will be different from the response of the individual accelerometer [1]. Some studies are being made about calibration methods for vector sensors (see *e.g.* [2]).

The advances in electronics and the miniaturization of devices have led to an increase in the development of underwater autonomous recorders. These devices are usually small and easy to deploy, being a good solution for underwater monitoring. Calibrating these devices presents some challenges since, in some cases, the transducers are attached to device body. All the structure needs to be calibrated to take into account the effects of the body in transducers' response. For low frequency calibrations, which are usually done inside a calibration chamber, to put the entire body inside may be problematic or even impossible. Another issue is that the transducers' output is not directly available for measuring so, the signal path from transducer terminals to recorded file should be well know and characterized for proper calibration. Some projects attempted to develop some equipment and methodologies for calibration with some degree of success, but standards are yet to be defined [3, 4].

This report will make a brief presentation about the standard calibration methods for hydrophones and accelerometers, in chapters 2 and 3, respectively. Then, focusing on the free field comparison method, the required equipment and the calibration procedure are described in chapters 4 and 5, respectively.

Chapter 2

Calibration methods for hydrophones

There are several standardized methods for hydrophone calibration, but the most common belong to two categories: the low frequency calibration and the free field methods. These methods are of simpler execution and require few equipment, when compared to more complex approaches that need some specific equipment and specialized facilities. These methods are often characterized as primary methods, when there is no need to use a calibrated transducer or secondary methods, when a calibrated transducer is needed. The sensitivity naturally changes along the transducer lifetime, so regular calibration must be performed to ensure correct measurements.

The free field method refers to the calibrations that can be performed in a medium without interference from the boundaries. Even if this approach is not easy to perform in practice, some approximations may be used. The use of a large body of water, like a tank or a quiet lake are the most common solution. However, a free field environment has some limitations such as the lowest frequency of signals, or the difficulty in achieving a quiet environment for calibration on open waters. When testing in a tank, the walls will act as a signal reflectors, and reverberation will interfere with the transmitted signal. To overcome this issue, it is common to use a pulsed signal with some number of cycles of a tone signal, but a low frequency tone signal will last more time than a similar (same number of cycles) higher frequency signal, which will reflect on the walls and overlap with the transmission. This severely limits the minimum frequency that can be used in a tank, usually at approximately 1 kHz. Lower frequencies can be achieved in a lake or open sea, where the boundaries are in the far field from the transducer, allowing more free time for possible reflections. But, the environmental conditions in open waters can not be controlled, and some interference from external factors may co-exist. For testing a transducer behaviour at lower frequencies, the low frequency methods are the solution, but they require some specific calibration equipment.

The next chapters will present a brief introduction of these methods.

2.1 Low frequency methods

There are several approaches for low frequency calibrations, usually below 1 kHz. The most commonly used are the pistonphone and the vibrating column method (figure 2.1), but methods as standing wave tubes [3], hydrostatic excitation, closed chamber comparison, couple reciprocity or piezoelectric compensation are also possible and well standardized methods [5]. In addition to these methods, some processing techniques are suggested in [6]. Most anthropogenic noise is within this frequency band, so in order to monitor underwater noise reliably the measuring device should be calibrated for these frequencies.

2.1.1 Pistonphone

A pistonphone is a calibration equipment for microphones and hydrophones. Pistonphone calibration is performed by inserting the hydrophone to be tested into a closed chamber filled with air, which contains some type of pistons to change the internal pressure. Then the hydrophone is exposed to a sinusoidal pressure field, allowing the pressure sensitivity to be determined. It may be used for frequencies between a few hertz (Hz) up to several hundred Hz [4, 7].

2.1.2 Vibrating column

In the vibrating column method, the hydrophone is placed in the middle of a liquid column which is vibrated by some transducer or mechanical generator. The sensitivity is calculated from the pressure at the hydrophone depth and the voltage at its terminals. This method may be used to a frequency range from 10 Hz up to 2 kHz [4]. This method can be used for calibration of pressure hydrophones and vector sensors.

Equipments 1.jpg

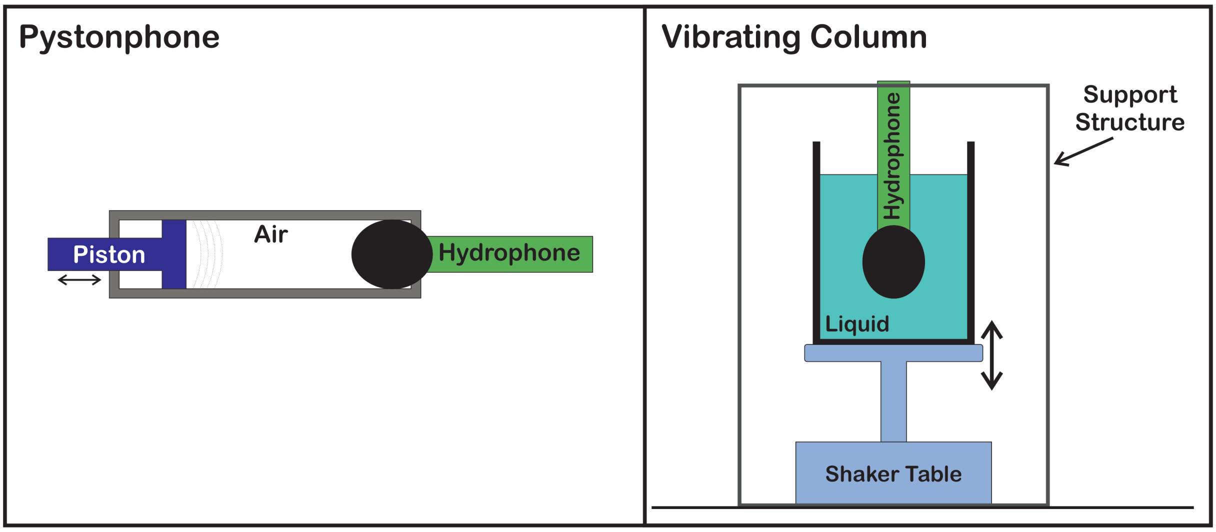


Figure 2.1: Low Frequency Calibration Methods, schematic for pistonphone (left) and vibrating column (right)

2.2 Free field methods

Free fields methods are based on the concept of free field, *i.e.*, the idea of measuring the response of a transducer to a plane wave incident from a given direction and free from any reflections or scatterings that can distort the original signal [4].

A sound field is established in a water medium as a spherical wave emanating from a projector. If a receptor is placed far enough from the projector, the segment of the spherical wave that reaches the receiver is small enough (large radius of curvature), so that segment is indistinguishable from a plane wave (check figure 2.2). The distance at which a sound wave segment can be considered plane is called far field distance r, and is a distance greater than the squared aperture size of hydrophone L divided by twice the wavelength λ of the used signal (Rayleigh distance) [8]:

$$r \geq \frac{L^2}{2\lambda} \tag{2.1}$$

Equipments 2.jpg

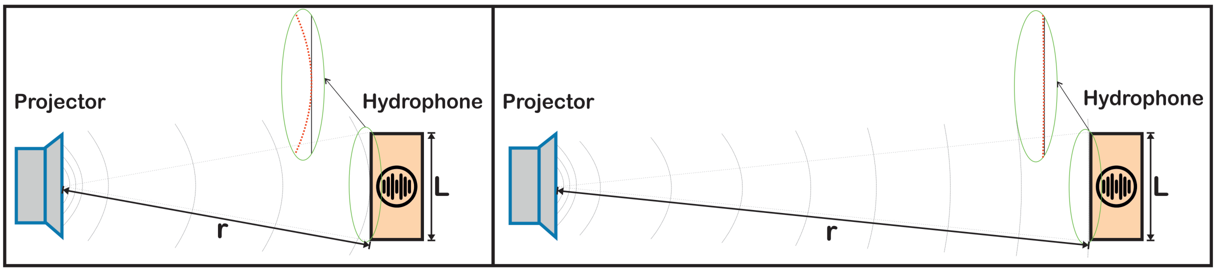


Figure 2.2: Free Field representation of a plane wave. Left side image shows a spherical wave in near field, where the wave curvature can be seen (dashed red line). Right side shows the receiver at a far field side showing that the wave is approximately plane.

The free field condition happens when waves are travelling in a homogeneous isotropic medium free from boundaries, even if in reality this can never be achieved. However, an approximation where the negative contributions from all the possible causes of noises can be minimized or eliminated, is usually good enough for calibration purposes [9]. Free field calibration methods require a facility that has a large volume of water, allowing an approximation of free field conditions and ensuring that the reflections from the boundaries do not affect the measurements. The reflections from boundaries can be gated out using a combination of tone burst signals and windowing techniques or signal post processing. By monitoring the driving voltage of the projector and receiver and knowing it's characteristics, the sensitivity of the system can be determined [7].

There are two common methods used: calibration by comparison and calibration by reciprocity, as described below.

2.2.1 Reciprocity method

The reciprocity method is a primary method based on the spherical-wave reciprocity and requires three transducers operated in pairs where one is transmitting and the other one is receiving. A requirement is that one of the transducers be reciprocal, that is, the receiving sensitivity and transmitting response are related by some constant value [9]. These devices are labelled as a P (projector), H (hydrophone) and T (reciprocal transducer), and three setups are defined. For each setup, the corresponding transducer pair is aligned at a known distance, respecting the far field and free field conditions, and the electric transfer impedance is determined. The electrical transfer impedance, the separation distance, the water density and the acoustic frequency are then used to calculate the sensitivity [4].

This method does not requires the use of any calibrated transducer (primary method), however a series of measurements are needed to obtain all the data for calibration calculations [10]. The results are more accurate than those of the comparison method, even if the set-up and procedure are more complex [11]. We will not get into details, but in [8] or [5] there is a well detailed explanation of this method.

2.2.2 Comparison method

The comparison method (also called substitution method) consists in the use of a previously calibrated acoustic transducer, as being a reference transducer (secondary method). The sound field generated by a projector is measured at a point in the acoustic far field by a calibrated reference transducer. Then, this reference transducer is replaced by the transducer under test. The ratio of the open circuit voltages of the two transducers is equal to the ratio of free field sensitivities, allowing the sensitivity of the transducer under test to be determined [4, 5].

This method has one simple equation that relates the sensitivity of the known and unknown hydrophones. The voltage sensitivity of the unknown hydrophone (S_u) will be equal to the known reference hydrophone sensitivity (S_k) multiplied by the open circuit voltage of the unknown hydrophone (V_u), divided by open circuit voltage of the known hydrophone (V_k) [8, 9]:

$$\frac{S_u}{V_u} = \frac{S_k}{V_k} \Leftrightarrow S_u = \frac{S_k V_u}{V_k} \tag{2.2}$$

Or, in decibel units:

$$20 * log(S_u) = 20 * log(S_k) + 20 * log(V_u) - 20 * log(V_k) \tag{2.3}$$

This is the simplest method that can be quickly applied when a transducer properly calibrated is available [10]. When properly made, this method gives reliable and accurate results [9]. However, it is difficult to do in open sea due to the environmental conditions that can affect the measurements (sea state, wind, waves, several noise sources...). Usually it is done in a large tank or in a quiet lake.

2.3 Sources of uncertainty

Any measurement has an associated uncertainty, caused by the method itself or by the instrumentation equipment. When calibrating underwater equipment, the following error sources should be considered, and minimized whenever possible [5]:

- Electrical errors, coming from measuring instrumentation (linearity, RF pickup, cross talk, gains, frequencies), power source oscillations, changes in electrical behaviour due to thermal differences or cable loading.

- Underwater conditions, like water temperature changes, air bubbles, presence of marine life or anthropogenic noise sources.

- Method errors, such as transducer misalignment and distance variation, lack of free and far field conditions, uncertainty of reference device sensitivity, scattering sources or receiver steady state not reached.

This list is not meant to be exhaustive, and just provides a reference of the most common uncertainty sources. Each method or equipment will have its own sources of uncertainty. In practice, some of these errors are difficult to measure and quantify. All the measurement should be done several times to statistically treat the results.

2.4 Practical considerations

Any chosen method has valid results, however the best practice is to calibrate the device in similar conditions of those existing in the usage site. Following the standard recommendations are the best practice to get a correct calibration. Some practical advice for hydrophone calibration are [4, 12]:

1. Calibrate the hydrophone in the same support structure that will be used in the experiment site. This will allow the calibration response to take into account the effects of support structures, which can affect the signals. If possible use a support that does not affect the device sensitivity.

2. Try to replicate the temperature and pressure conditions of the deployment site, as some hydrophones may perform differently under distinct circumstances. After installation on the deployment site, allow the device to stabilize temperature before measurements.

3. Do a process called "wetting" to the hydrophone, before the calibration procedure. This allows the cleaning of the surface and prevent the adhesion of dirt, grease and air bubbles that can interfere with the measurement. This is done by washing the sensing element with a wetting agent, then immerse and remove it from water. Then quickly check for dry areas that should not be visible. If there is any dry areas, the cleaning process should be repeated.

Chapter 3

Calibration Methods for Accelerometers

Accelerometer calibration methodologies are standardized in ISO16063 (Methods for the calibration of vibration and shock transducers) [13]. This standard is composed of several parts, each one dealing with some property to test or test methodology. There are four primary methods defined, based on reciprocity method (part 12), laser interferometry (part 11), earth's gravitation (part 16) and centrifuge method (part 17). A secondary method, based on comparison calibration, is defined in part 21. We will not detail how these methods are deployed.

The simplest method for calibrating an accelerometer is to use the comparison method. This consists in using a calibrated transducer as a reference and comparing its output voltage to that of the calibrated device, when both are exposed to a similar acceleration (similar to hydrophone free field comparison method)[14]. During testing the transducer is usually fixed to a vibration generator that oscillate with some displacement, velocity and frequency. The knowledge of the device acceleration is not required, since it can be obtained from the calibrated transducer. This procedure should take into account the desired test axis. More accurate calibrations can be done using primary methods however they are expensive and for the most common cases the results from comparison method are good enough [15].

The most relevant characteristics to be measured are the sensitivity, frequency and phase response, linearity, temperature dependency and cross talk between perpendicular axis (called transverse sensitivity ratio). Some of these characteristics can be dependent on the axis tested. The accelerometer data sheet will present these specifications, as measured by the manufacturer.

It is important to note that these calibration methods and performance metrics are defined for air calibrations and for the transducer itself. When using underwater and within a structure, for example as an underwater vector sensor, the device behaviour can be completely different hence the need for a proper in place calibration.

Even though there is no standard defined for underwater accelerometer calibration, there is a simple way to do it. Assuming that the comparison method for hydrophones was used for some calibration experiment on a device containing an accelerometer (as a vector sensor). If we want to calibrate an accelerometer we can relate the voltage obtained on the accelerometer with the reference hydrophone voltage. This relation is called pressure equivalent sensitivity $S_{p_{eq}}$ and is based on accelerometer voltage $V_{RMS_{acc}}$, reference hydrophone RMS voltage $V_{RMS_{ref}}$ and reference hydrophone sensitivity S_{ref} [8]

:

$$S_{p_{eq}} = S_{ref} + 20log10(V_{RMS_{acc}}) - 20log10(V_{RMS_{S_{ref}}}) \tag{3.1}$$

The obtained value is then linearised and referred to μPa units:

$$M_p = 10^{\frac{S_{peq}}{20}} * 10^6 \tag{3.2}$$

And finally the accelerometer sensitivity M_a $(V/(m/s^2))$ is obtained through the relation of the acoustic impedance ρc and the pulse frequency of the signal f, with the pressure equivalent sensitivity M_p (water density, depending on the test site but near $\rho = 1026\ kg/m^3$; speed of wave in water, around $c = 1500\ m/s$):

$$M_a = \frac{\rho c}{2\pi f} * M_p \tag{3.3}$$

Note that what is described above, where the media impedance is a pure real number, is only valid under the plane wave assumption and far from the source and any boundaries. Otherwise the acoustic impedance should be considered as complex and the velocity and pressure are no longer in phase.

Chapter 4

Equipment for underwater calibration and autonomous recorder characteristics

In this chapter we will describe some the most commonly used equipment for a calibration experiment, and also some important metrics for their characterization.

For the standard hydrophone calibration with comparison method some instrumentation equipment is required, in order to capture the voltage response. Besides the calibration method, the used equipment and some of its characteristics are important to know. For vector sensors no standard calibration methodologies exist, so the common approach is to use the hydrophone methods and perform the calibration based on those. Here we will consider the free field comparison method, due to its practicability.

It is important to note that some vector sensors are a complete acquisition system, so that the transducers and all the electronics are inside the device body. Since the transducers are physically attached to the device, the calibration must be done to the system as a whole. This will show whether there are any reflections or resonances caused by the device body which can affect or interfere with the acoustic measurements [16]. Calibrating such a system have some constrains as for example the fact that we can not directly measure the transducers' output. So, all the device measurement must be done and stored to later analysis, not only from the acquisition system but also from external devices such as oscilloscopes or signal generators.

Following there are some basic concepts for measuring instrumentation characteristics and metrics.

4.1 Measurement instrumentation and components

For the calibration procedure using the comparison method, some additional equipment is required. Depending on the devices available, but the most common components used for calibration are:

- Acoustic transducer, as source of sound waves.
- Amplifiers for emitter and receiver transducers.

- Filters to remove unwanted frequencies (optional device).
- Oscilloscopes to digitise the analog signals.
- Data storage devices, to store the digital signals.

Figure 4.1 shows the most common setup for calibration of underwater transducers. The real connections can be distinct, depending on the used instrumentation devices. The equipment shown is briefly described in the following subsections.

Calib Equip.jpg

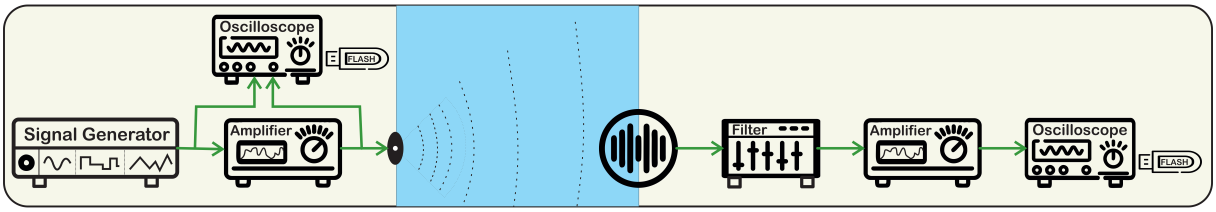


Figure 4.1: Common setup schematic for calibrating underwater acoustic transducers using comparison method. The blue part represents the water body.

4.1.1 Acoustic transducer

Besides the receiving device, a projector or transducer needs to be used to transmit the calibration signal through the medium. This can be a calibrated device or not, depending on the experiment. It is possible to use a calibrated projector to do the calibration experiment, knowing the distance between the source and the receiver as well as the projector transmitting voltage response (TVR). The TVR is a metric used to describe the transmitting response of a device, in terms of sound intensity generated when some voltage is applied. This metric is provided by the device manufacturer and should be available in the device data sheet. There are more electrical parameters that characterize a transducer, but they are not so important for calibration.

4.1.2 Signal generator

A signal generator is used to create a specific signal which will be sent to a sound source, usually through an amplifier. An appropriate signal generator for underwater applications will allow the creation of pulsed signals or sweeps with several shapes, amplitudes and frequencies. The output of this device has a low voltage level or low power, therefore, it can't be directly connected to a projector, being necessary to go through a conditioning stage to adapt and amplify the signal. During an experiment the waveform shape, frequency, amplitude or any important device setting must be stored.

4.1.3 Amplifier

Amplifiers are used to increase the low amplitude signals coming from any device, so that signals can reach the appropriate level for the following stages. The common performance metric used is gain which could be a linear gain (e.g.: x2) or a decibel (logarithmic) gain (e.g.: 3 dB). The gain of an amplifier is frequency dependent, however for the usable frequency band it's common to define a linear zone, where the gain is nearly constant.

In the calibration setup an amplifier should be used to amplify a signal generator signal to the power levels required by an emitter source. In the receiver side, this can be useful to amplify the low power signals received by any transducer (hydrophone or accelerometer). In any case, the chosen gains should be annotated for later analysis, as they will be part of the conversion process.

4.1.4 Oscilloscope or similar capture device

To capture the output of hydrophones, projectors or amplifiers, an oscilloscope with waveform storage is necessary. This device will allow the recording of reference and test transducers' voltage output for later comparison and sensitivity calculation. It will also be useful for recording the emitter waveform, depending on the experiment. Some devices include the settings in the stored files metadata, otherwise those must be stored manually for the analysis process. For any type of capture device, it is important to know the amplitude and time scales of the recorded data.

When calibrating an autonomous recorder, the transducer output capture is done by its internal analog to digital converter (ADC). The ADC will convert all the analog signals coming from transducers, digitise and store them in any type of memory. It is important to know the characteristics of the recorder electronic components, such as the ADC, which can change and adapt the output signal of transducers. They may have any type of filters, amplifiers or signal conditioners internally, that we must be aware of for the correct conversion of values. Also, the used settings such as sample rates, cut off frequencies or gains must be recorded by some means. Some devices record this information along the main data file, but we must know that prior to the experiment.

4.1.5 Filters and signal conditioners

These devices adapt the amplitude or the frequency range of a signal that can pass to the next stage. Filters are used to remove or equalize unwanted frequency ranges, and can be low pass, band pass or high pass according to the passing frequencies. The filter response varies with frequency and should be characterized for the operating range of the system. There could be also some signal conditioners, which will adapt the voltage ranges from different stages. This information are available from the device manufacturer.

4.1.6 Data storage

This is not part of the instrumentation itself but as an important stage, the data storage is where the recorded data will be physically maintained. There several support medium like SD Cards, hard drives or cloud services, but what is important to known is the data file format. After the digitisation stage the data should be stored in any format that is lossless, without any compression that could affect the data quality. There is no standard format for storing underwater acoustic data, but the WAVE format is open source and guarantees wide and future compatibility [4].

Also, any additional data or metadata required to interpret the data signal of interest must be stored. The metadata are all the recorded data that do not directly represents the signals of interest but are useful to characterize the experiment. Settings such as amplifier gains, sampling frequency, device arrangement or any other relevant information for calibration must be stored, in the file header or into a log file, so that the information is kept with the data. Sometimes this information is not stored by devices, and the operator should record it manually. For calibration, the conductivity, temperature and salinity (CTD) of the water, as well as the device positioning (axis orientation, depth, etc), device fixation and site characteristics (like size tank, if the calibration is done in a tank or sea state, wind state or tidal range for open water calibrations) are important information to keep. Also, all the instrumentation settings are important to record, for later analysis. Since no standard is defined for this data, it should be recorded in WAVE file format itself whenever possible, or the operator should record it manually and store it with DATA files and in some easily readable format (like csv or txt). Can also be used a logbook of the experiment, where the operator must record all the important parameters and settings used. An example of a logbook is presented in appendice A.

4.2 Autonomous recorder characteristics and metrics

When dealing with an autonomous recorder there are some important characteristics to consider, that are common to any measuring device. Considering an autonomous recorder the most important characteristics are [17]:

- System sensitivity
- Frequency response
- Directional response
- Self-moise
- Dynamic range
- Maximum operative conditions

There are other electrical characteristics not listed here, specific for parts of the system. For example an hydrophone will have its electrical impedance, which will not be directly reflected in the recording characteristics. When dealing with an autonomous recorder, we do not have direct access to the transducers output, so we can not directly measure the output voltage. The calibration calculation should consider the signal path from the transducer till the digital recorded samples, and the possible signal manipulations done to the signal through this path. Not only the sensitivity of the transducers should be considered, but the whole system sensitivity, which for some devices may change with user settings [16].

4.2.1 Sensitivity

Sensitivity is the rate of conversion of a physical quantity into electrical voltage. For an hydrophone this conversion is the acoustic pressure (the input of hydrophone) into electrical voltage (the output), while for an accelerometer it will be the applied acceleration converted to a voltage value. The more sensitive the transducer is, the more voltage it will generate at its output, for the same physical input quantity. For an autonomous recorder the system sensitivity must include all the gains from all the electronic components.

Ideally, the sensitivity of the transducer and the measuring system should be chosen to have an appropriate value for the amplitude of the expected signals being measured. Quiet sounds will require a more sensitive hydrophone than loud sounds. The objective in choosing the system sensitivity is to:

- avoid poor signal-to-noise ratio for low amplitude signals;
- avoid nonlinearity, clipping and system saturation for high amplitude signals.

The sensitivity is frequency dependent, so the output voltage of a given device will change based on the frequency of the incident wave. It is common to specify the usable frequency ranges within a 3 dB range, meaning that the sensitivity will oscillate only between these values [18]. The sensitivity can also be directional, as with vector sensor where the response depends on the incident direction of sound waves.

A calibration experiment will allow to obtain this value for several frequencies, and eventually define the device frequency range.

4.2.2 Frequency range (bandwidth) and frequency response

Frequency range is the usable frequency band (bandwidth) of the system, between a minimum and maximum value. This range of values can be limited by some other characteristics, such as the sensitivity. For example, the frequency range can be based on the sensitivity values, where the sensitivity should be considered linear, within some tolerance level (usually 3 dB), as in figure 4.2.

The frequency response will show how the device output level dependence with frequency. Usually it is expected that into the bandwidth of the device, the level remain stable within a small tolerance, the so called linearity. The device can also have some resonance frequency(ies) which should be avoided during normal operation, since they can cause problems into measured signals (see the peak in figure 4.2).

Once again, those properties are different for individual devices and for the complete system. These characteristics are available from devices manufacturer. An autonomous recorder should be tested as a complete system in order to determine whether the body and device components affect the whole system behaviour.

The frequency range for testing will depend on the objective of the measurement and characteristics of the system. The chosen sampling rate of devices' ADC, must be at least the double (normally 2.5 or 3 times) of the maximum required frequency. For example, if our measurements require a maximum frequency of 4 kHz, a sampling rate higher than 8 kHz must be chosen. Of course, this will depend on the systems hardware specifications, that should be considered when choosing or configuring the device. If our system has a maximum sampling rate of 12 kHz, we can only capture frequencies above 6 kHz, a property that is related to Nyquist theorem and is outside the scope of this text. Also check the system minimum frequency, which for some underwater application can be a very low frequency (ex: 10 Hz).

4.2.3 Directivity

Directivity is the property of a transducer to be more or less sensitive in one direction then another. It refers to the variation in sensitivity relative to the angle of incidence of the acoustic wave on the sensing element. An hydrophone normally has an omnidirectional response (sensitivity invariant with incidence angle) in some plane (horizontal or vertical), inside some tolerance limits and for some frequency range. An accelerometer will have a response which is directional and based on the intensity and frequency on the incident waves for each axis. In a complete acquisition system these properties must be tested for each axis plane, since there will be possible interference with the body that must be characterized.

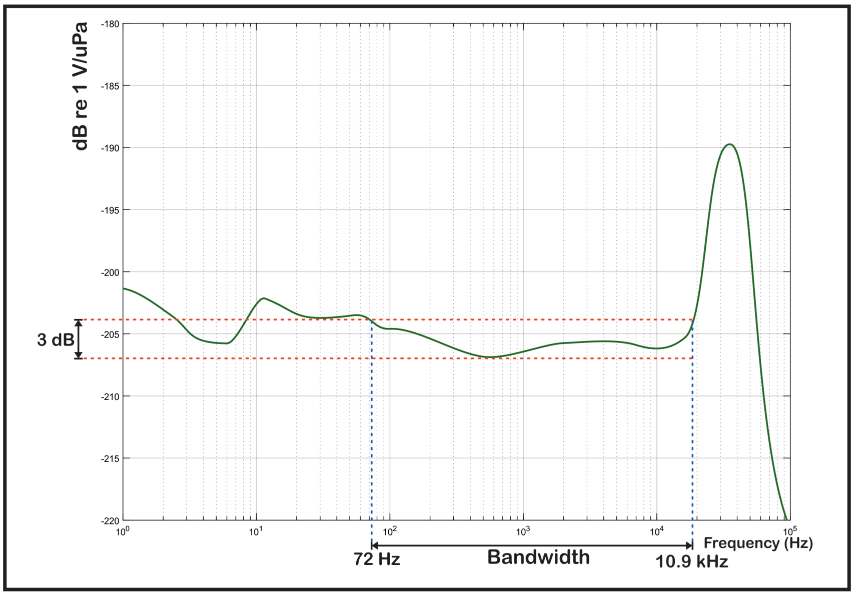
Spectrum example 1.jpg 

Figure 4.2: Sensitivity and frequency response example.

4.2.4 System self-noise

The self-noise of the system is an important parameter when measuring underwater ambient noise. Self-noise is the noise that the equipment produces itself, when no acoustic signal is present. It represents the lowest levels that can be recognized in recordings, and varies with frequency. It is usually expressed in a noise equivalent sound pressure level in dB re $\mu Pa^2/Hz$ or $\mu Pa/\sqrt{Hz}$. This should be at least 10 dB below the lowest signal to be measured, in order to guarantee a sufficient signal to noise ratio.

Self-noise arises at least from two sources: (i) noise generated by the transducer and recording system, electrical noise; (ii) noise generated by the deployment platform, attachment or mooring. The electrical self-noise can be measured by placing the system in an acoustically isolated room and recording data for some time interval. The equipment must be operated from batteries and any other electrical equipment should be removed from the room, limiting any induced electrical noise from the surrounding environment [19].

4.2.5 Dynamic range

The dynamic range of the system is the amplitude range over which the system can measure the sound pressure. It will range from the lowest signal that can be measured (limited by the system self-noise) to the maximum amplitude that may be measured without distortion.

When measuring low amplitude signals these should exceed the noise floor of the system, and the ADC should provide sufficient resolution to decrease the quantization error for small signals. Also, it should be considered that some high level signals could corrupt the normal signal (*e.g.* a boat passing by) that may cause saturation or clipping of the signal. Some prior knowledge of the acoustic signals should be considered, to optimize the dynamic range.

Note that at frequencies well below the resonance frequency, the hydrophone sensitivity should be invariant with frequency. However, as an hydrophone approaches its resonance frequency, the sensitivity cannot be considered to be “flat” and is likely to show variations in the response.

4.2.6 Maximum operative depth, pressure and temperature

The properties of transducer material and system body may suffer significant changes with pressure and/or temperature variations. The operating ranges of the measuring device in terms of pressure, depth and temperature, are usually given by the manufacturer and must be respected to avoid device failure or bad readings. These characteristics should match and exceed those expected at the deployment site. If calibrating a device for a specific use, the same conditions of the deployment site should be replicated into the calibration experiment, in order to minimize uncertainties. Also, after placement on site the device must be powered and given some time to stabilize the system before starting the experiment.

Chapter 5

Calibration with the free field method

The commonly used method for underwater sensitivity calibration is the free field comparison method. This method does not require any specific test equipment, beside a calibrated transducer. However, in order to obtain the required free field conditions the experiment must be performed in a place with a large volume of water such as the open sea, a lake or a big tank. Each of one of these environments have distinct characteristics that should be taken into account when planning a calibration experiment. A tank is commonly used, since the environment conditions can be easily controlled. However, there are some limitations for lower frequencies. A lake or open sea environment can have ambient noises (ship traffic, waves, rain, etc), ocean currents and temperature changes, marine life interference, air bubbles from breaking waves or pollutants, which can affect the measurements and, most often can not be controlled.

For the sensitivity calibration, a reference transducer is fixed in a place and some pulsed signals are transmitted with a projector. The voltages at the receiving transducer terminals are captured with an oscilloscope. Then, this reference transducer is changed for the one to be tested, placing it exactly on the same position. The same signals are sent and recorded. For the directivity calibration the same pulsed signal can be used, but no need to use a calibrated transducer. The testing device is placed at a fixed distance from an emitter and rotated around its axis, while the emitter is sending pulsed signals. A complete turn over a given axis must be made and the output recorded in order to obtain a directivity plot. This is repeated for all axes. Next we will discuss some important information for these calibration experiments, namely the pulsed signals and the underwater calibration sites.

5.1 Calibration signal

The signal used for calibration purposes is usually a pulsed signal containing a single frequency sine wave (the tone signal), which is repeated at regular intervals (pulse repetition period). As seen on figure 5.1, a sinusoidal signal is gated by a rectangular pulse, generating a pulsed output signal. The gating signal is related to the tone signal frequency, since the gating should last an integer number of cycles. This signal can be generated by any device (*e.g.* a computer or a signal generator) and will be forwarded to the projector, passing through an amplifier. The amplitude at the output of amplifier can be monitored and recorded. In that example, the gating signal lasts for 10 complete sinusoidal cycles. That number defines the pulse length. The duration of the pulsed sig-

Waveforms Simple.jpg

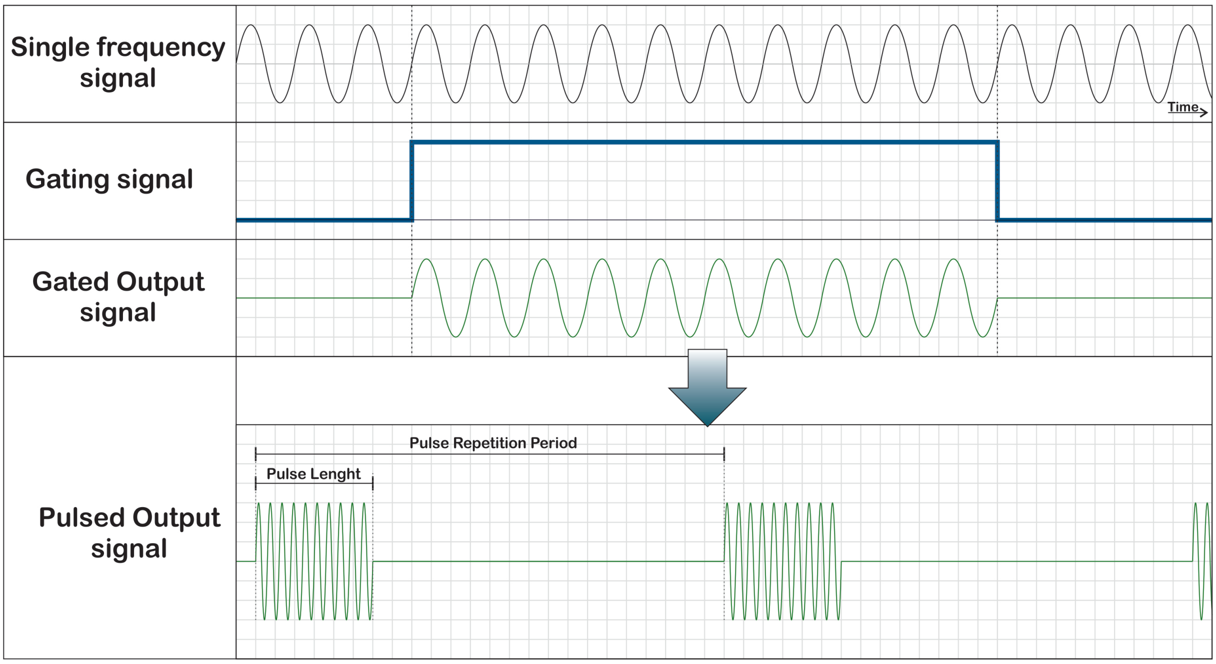


Figure 5.1: Pulsed Signal components.

nal (t_{pulse}) is based on how many cycles are used (N_{cycle}) and the tone signal frequency (f_{signal}):

$$t_{pulse} = \frac{N_{cycle}}{f_{signal}}[s] \tag{5.1}$$

The pulse repetition period $t_{repetition}$ is chosen based on the last reflected signal time and should be adjusted to allow for all reverberation components to completely decay [11]. The first reflected signal arriving to the hydrophone depends on the calibration site boundaries and the positioning of the equipment on the test site. The pulse repetition rate PRR is the inverse of the pulse repetition period ($t_{repetition}$):

$$PRR = \frac{1}{t_{repetition}}[Hz] \tag{5.2}$$

The PRR should be low large enough to allow for the dissipation of all reflections between pulses [9]. The pulse length can also be written as a percentage of the repetition period, called duty cycle DC_{pulse}:

$$DC_{pulse} = \frac{t_{pulse}}{t_{repetition}} * 100[\%] \tag{5.3}$$

The received pulse has some transient time before reaching the steady state, where the signal remains at a constant amplitude. The pulse length should be long enough to attain this steady state voltage amplitude at the output of the receiver. The waveform measurement needed for calibration are performed from this steady state part of signal. To avoid the overlapping of direct and reflected waves, the end time of the steady state part of the direct path pulse, must be smaller than the first reflected pulse arriving at receiver. In the end of the pulsed signal there is also some decay time. This behaviour is related to device resonance [5]. How many signal cycles are needed to achieve steady state is usually defined as the Q factor, being a characteristic of the transducer [9]. Figure 5.2 shows a perfect pulse to represent the transmitted and received signal, but note that in reality, even the emitter will suffer the same behaviour.

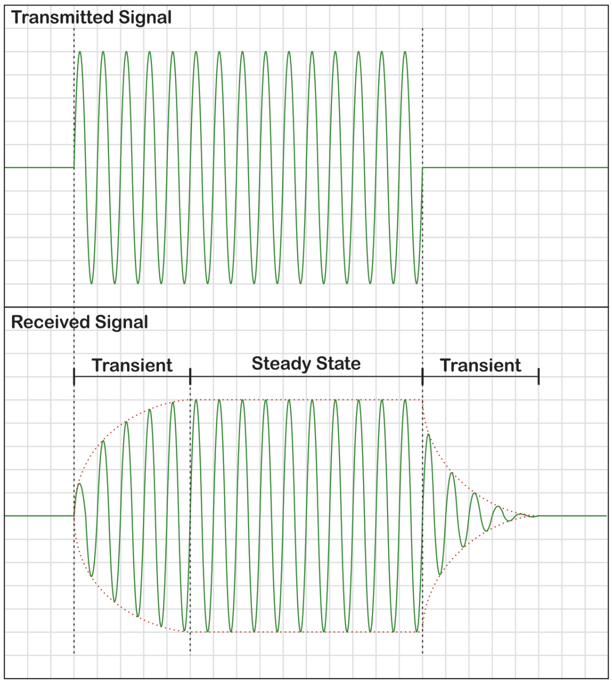
Waveforms Signal trans Receiv.jpg 

Figure 5.2: Example of a transmitted pulse (ideal) and received pulse without interferences, showing the transient and steady state parts of signal.

5.2 Tank calibration

A simple solution for underwater calibrations is to use an anechoic water tank, with absorbent walls. A tank has a big advantage in calibration experiments since all the conditions can be controlled and most of the noise sources eliminated. However, the boundaries and the small distance between them and the equipment will cause reflections of the signal. This must be considered, especially when a continuous signal is used, since the reflected signals could interfere significantly with the received signal. To overcome this issue a pulsed signal is usually used, which will minimize or eliminate the interference of the reflections.

When calibrating in a tank all the setup, tank sizes and devices placement must be considered, trying to minimize the reverberation at the receiver. This can be done by adjusting the characteristics of the pulsed signal to the tank sizes and transducers placement, namely in pulse duration (pulse length) and pulse repetition rate [11].

To better understand these constrains we will show some of the propagation paths in a tank and the effect of use a pulsed signal.

5.2.1 Tank propagation paths

In a tank experiment there will be mainly three types of signals: the direct signal, the reflection in the walls and the reflection in top/bottom. There could also be some scattering in any additional structure, as device supports, but we will ignore this for now. The test transducer will receive the direct and reflected signals at different times, based on tank size and how the equipment is positioned in the tank. The direct signal and the reflections can overlap and interfere mutually, and that's what we should avoid. The interference free time window should not have overlapping signals, at least till the end of the steady state zone of the pulse. This will allow the processing of the steady state zone in the direct path and obtaining the desired values without any interference. Figure 5.3 shows a simplified example of an emitted pulse and the same pulse at the receiver with reflections. In this case, no signal overlaps, for better understanding, however in practice ti may be difficult to achieve this condition (at least for the lower frequency range).

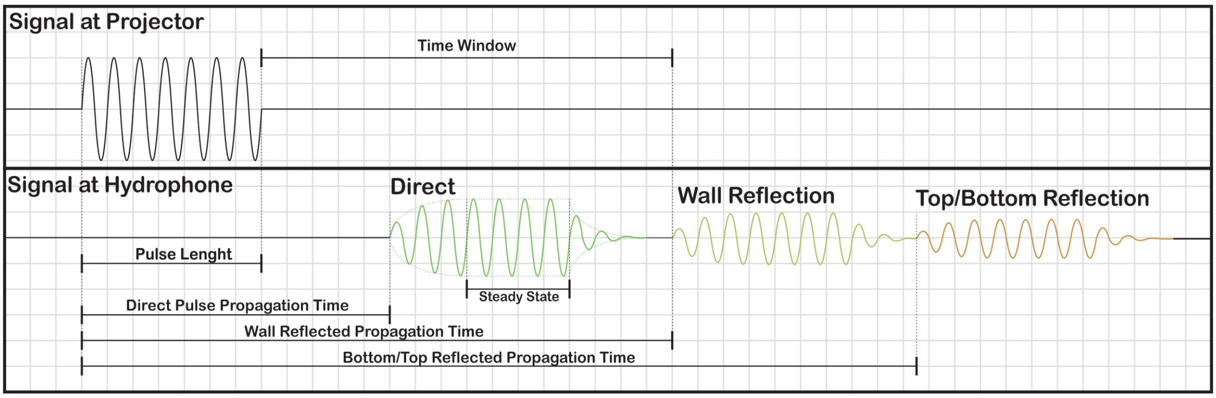
Waveforms.jpg 

Figure 5.3: Underwater signals example for a tank experiment with pulsed signals. On top there's a single pulsed signal which last 7 cycles. On bottom, there are the three types of signals received, with the propagation times marked. The time window represent the free from reflections time and steady state the area of direct signal used for signal processing.

In order to understand the tank size constrains let us look at how the signal wave propagate through the water, using some geometrical analysis. The distance between transducers should be in the far field zone, to assume a plane wave propagation. In figure 5.4 it can be seen three main signal paths, from any projector source to a hydrophone, in a tank of sizes L_{tank} X d_{tank} (length X depth meters). Figure 5.4 is a lateral view of the tank, in a simplified situation with the devices at the same depth. For the images (1), (2) and (3), the devices are aligned at the middle depth of the tank and the distance between them is large enough to assume they are in the far field zone. Devices can also be at different heights, and the same geometrical analysis can be made. The first path (image 1 of Figure 5.4) is the direct path ranging L_{direct} meters. The time it takes for a pulse to reach the receiver (t_{direct}) depending on the water sound velocity (c_{water}) follows the formula:

$$t_{direct} = \frac{L_{direct}}{c_{water}}[s] \tag{5.4}$$

The second path (image 2) is the reflected signal from the wall behind receiver ($t_{wall-reflected}$). This corresponds to the time it takes a pulsed signal to travel the direct path distance L_{direct} plus twice the distance between receiver and the wall ($L_{hyd-wall}$):

$$t_{wall-reflected} = \frac{L_{direct} + 2 * L_{hyd-wall}}{c_{water}}[s] \tag{5.5}$$

The third path (image 3) represents the reflected waves from wall behind projector and can be found using equation 5.5. Some projector transducers are omnidirectional, so this reflection must be taken into account. If the projector is unidirectional, this reflection can be neglected.

The fourth path (4) of figure 5.5 shows the top and bottom reflected paths, which for the projector and hydrophone placed in the middle of the tank, will travel the same distance. However, note that the two signals can be completely different and will interfere mutually at the receiver. The distance covered by the two waves will be based on two alibration tank$_m$*easures1.jpg*

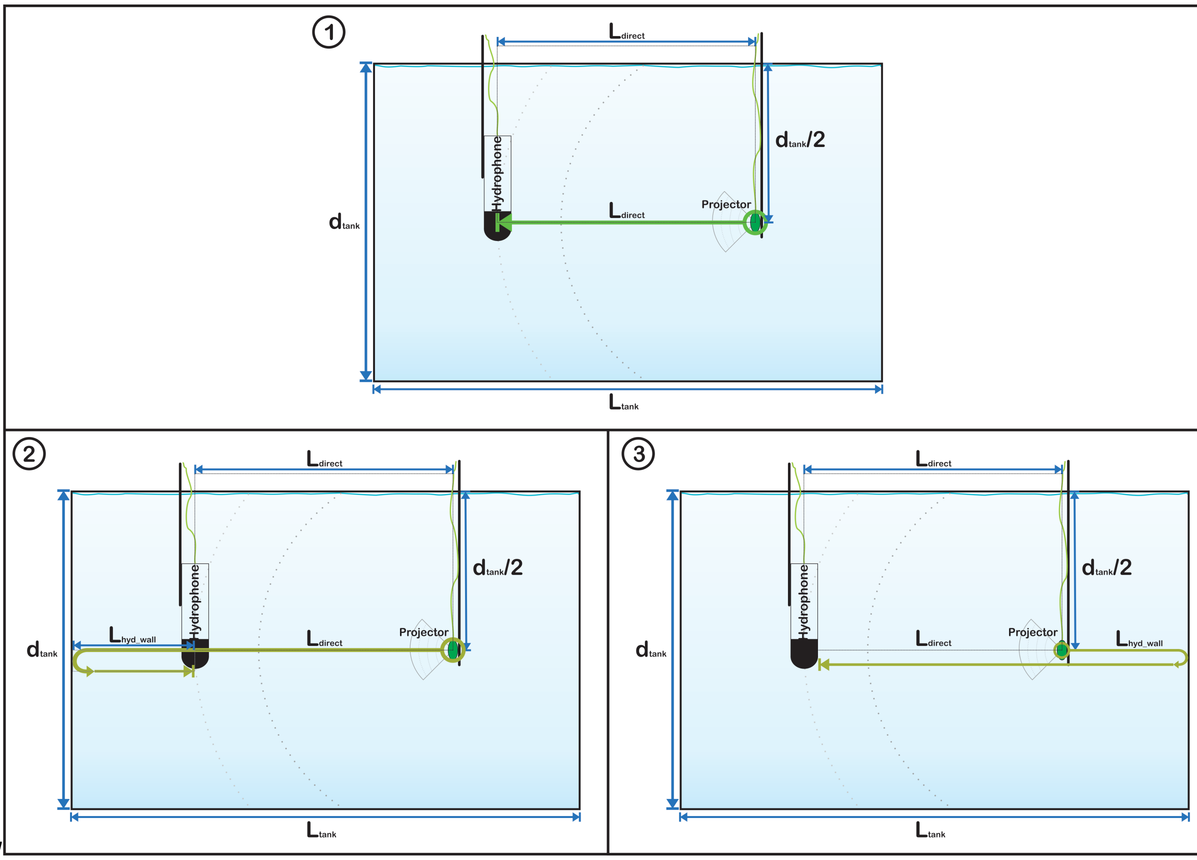


Figure 5.4: Propagation path for three situations, with source and receiver at same depth. 1) direct path; 2) The wall behind receiver reflection path; 3) the wall behind emitter reflection path.

triangles decomposition, with height of $d_{tank}/2$ and length of $L_{direct}/2$:

$$L_{reflected} = 2 * \sqrt{\left(\frac{d_{tank}}{2}\right)^2 + \left(\frac{L_{direct}}{2}\right)^2} \tag{5.6}$$

which will result in a propagation time of:

$$t_{top-bottom-reflected} = \frac{L_{reflected}}{c_{water}}[s] \tag{5.7}$$

If the projector and hydrophone are placed at different heights than the middle tank, as in image (5), the signals paths will be well separated in time, since they will travel completely different distances. The two signals travelled distance can be found the same way, but for each of the travel distances.

$$t_{top-reflected} = \frac{2 * \sqrt{(d_{transducers})^2 + \left(\frac{L_{direct}}{2}\right)^2}}{c_{water}}[s] \tag{5.8}$$

$$t_{bottom-reflected} = \frac{2 * \sqrt{(d_{bottom})^2 + \left(\frac{L_{direct}}{2}\right)^2}}{c_{water}}[s] \tag{5.9}$$

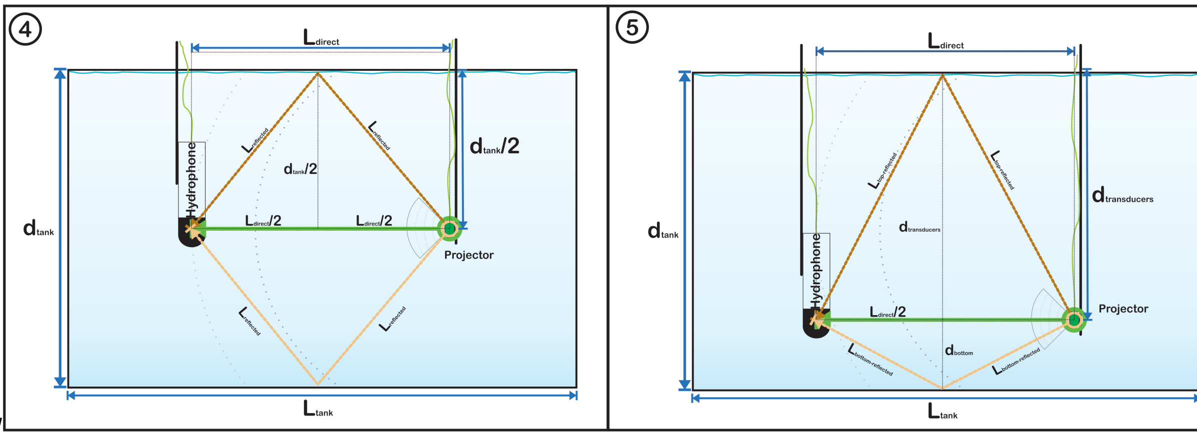
alibration tank$_{m}easures2.jpg$ 

Figure 5.5: Propagation path for: 4) top and bottom reflection with transducers placed at mid depth of tank; 5) Transducers at a different depth than the middle of the tank depth

With $d_{transducers}$ being the distance between top of water and the transducers (depth), and d_{bottom} the distance between the transducers and bottom of the tank.

In a real tank there are also some lateral reflections. These latter formulas (eq. 5.7, 5.8 and 5.9) can also be used to find the lateral propagation time, between transducers and side walls of a tank.

5.2.2 Tank calibration limitations

Even though tank calibration can be free of external non-controllable noise and interference factors, some limitations still occurs. The most significant is the lowest frequency that can be used without interference, which for a tank is usually limited to around 1 kHz due to tank reverberation interference [5]. Some processing techniques has been developed to reduce this lower limit without using any additional equipment [20].

At higher frequencies the signal can get significantly attenuated due to water absorption. But the biggest limitation comes from far field condition, which change with signal frequency. The higher the signal frequency, the greater distance is required to achieve far field conditions. However a longer distance between transducers lead to a lower free reflection time window. A good balance between the transducers distance and the maximum frequency should be achieved.

5.3 Open water calibration

In order to overcome tank low frequency limitations, calibration may take place in a large volume of water like a quiet lake or even at sea. There are several facilities around the world were calibrations of underwater devices are done in lakes. These facilities provide some type of floating platforms, where the electronic instrumentation is housed and where the tests are performed (figure 5.6). Sometimes these platforms can oscillate causing motion errors in measurements. To overcome this issue, in some regions, an ice covered lake may be used, which provide a stable platform to work from as well as reduced motion errors on the calibration data. It also helps in maintaining a fixed horizontal distance [2]. However, the ice itself can be a source of noise depending on the environmental status (if ice is melting, for example).

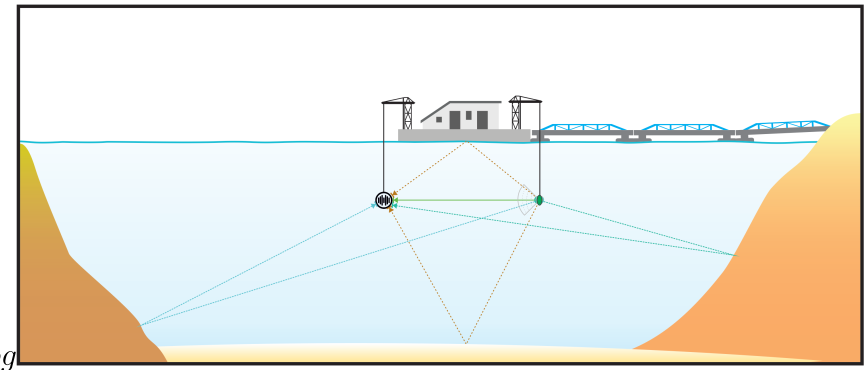
Calibration Open Water$_{l}ake.jpg$


Figure 5.6: Schematic of a typical calibration facility in a lake. The basic reflection paths are represented. Note that more reflection sources can exist (not to scale).

It is also possible to do calibration experiments from ships, even if they are less stable and add additional difficulty in keeping the transducers in the desired position (figure 5.7). A big issue is the difficulty in maintaining the boat position, due to surface waves. At the same time, most of the experiments are done using a flexible cable to support the transducers. If there is a need to align the orientation of a transducer to a specific axis, such as for a directional response test, this can be very challenging if not impossible. A rigid structure that allows the device alignment, can be hard to deploy in practice due to the desired deployment depth.

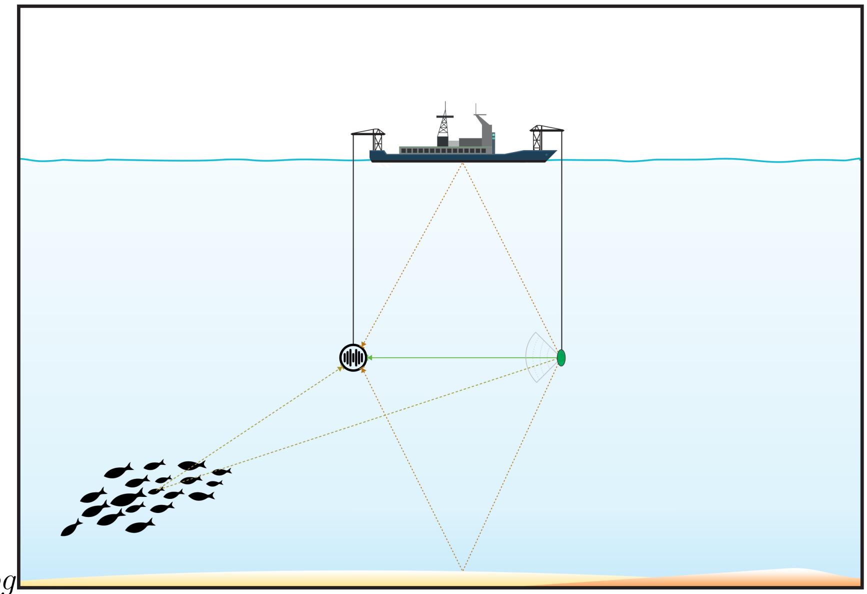
Calibration Open Water$_{s}ea.jpg$


Figure 5.7: Schematic of a typical calibration experiment in open water, using a ship. The basic reflection paths are represented. To note that more reflection sources can exist (not to scale).

When planning calibration experiments in open water facilities, some requirements need to be addressed: 1) the use of a water reservoir large enough to minimize reflections from boundaries, 2) a low noise environment, without noise from anthropogenic sources and 3) a medium free from sources of scattering and refraction (air bubbles, temperature gradients, pollution, marine life). These two last points are difficult to achieve and are not controllable, which justifies for almost all the calibration facilities using a large tank where the environment is easy to control.

The signals and sound propagation follows the same rules as for the tank experiments. However open waters present the problem of water temperature gradients, where the propagation velocity can change with depth which should be considered during testing. These gradients may cause the variation of sound speed and even create propagation channels (when considering the pressure, and depending on the depth), that for the calibration purpose, are not useful. In order to know the water column temperature at deployment site some additional measurements must be done to log water conditions. A good place must have stable conditions, that will not change during the experiment.

The top and bottom surfaces are usually better reflectors than those of tanks, since no absorbing material can be used. Specially the bottom, which depend on the geometry and material that can be highly reflective. However, the large depth and lateral dimensions will minimize the reflections caused by lateral boundaries. This will allow to use a signal with a lower frequency, due to a longer time without reflections. The same calculations as those used for the tank may and should be used. Figures 5.6 and 5.7 show the basic acoustic wave propagation paths. Note that these figures are just representative, each deployment site will have it's own distances and conditions that must be known. The additional source of reflections and scattering are omitted from the images, but should also be considered.

5.4 Calibration experiment considerations

To execute a calibration experiment using the comparison method, some prior considerations must be taken into account. Before planning the experiment, one should try to identify the site characteristics namely dimensions (depth, lateral sizes), site type (tank, lake, sea) and conditions. Attempt to know prior to the deployment, whether the site has any support structure or fixation, and how these are made (design, materials, sizes). Check if there is any platform to support devices and what mobility can be achieved (translation, rotation or fixed). Check also for position accuracy.

Then, and considering the test site, prepare a test plan identifying the following information:

- The objective of the experiment, which measurement must be done (sensitivity, directivity or others).
- What resources are required for the experiment. Make a list of all the equipment needed and identify it by reference transducers (calibrated), transducers to test, amplifiers, filters, data digitizers (*e.g.* oscilloscope with external storage), cables, power sources, fixation material, etc. Collect this material in advance and double check for missing items before leaving to deployment site. When there are several identical devices which can have different responses, it is important to identify that specific device using *e.g.* the serial number. Use this list also as a check list, before leaving to deployment site to confirm that you have all the material needed.
- Try to establish a plan of the activities with a timeline, of what should be done and when to execute the experiment. Plan times with some margin and if possible, establish a contingency plan.
- Define the signals to be used (signal type, PRR, amplitude), based on the deployment site characteristics. If using a programmable signal generator, generate all the code needed for the experiments, program, and test it locally some days before the experiment.

During the experiment, try to follow the plan and assess if there are any constrains that can affect the experiment. Some practical considerations are:

- The first experiments should be done to evaluate the chosen settings and testing the setup; Take some time to see if the emitter amplitudes and received signals are in acceptable ranges for later processing. If there are any problems during these tests, they can be adjusted and do not compromise the whole experiment.
- When mounting the device in the support structure respect the axis defined for the experiment. Small variation in the alignment can cause big issues in the captured signal.
- During the experiment, record any changes in the setup and settings, as well as the names of recorded files. Take some relevant photos of the experiment, such as the fixation supports, device positioning or the setup used to capture data. Appendix A contains a sample logbook that can be useful for a calibration experiment.

After the experiment, recover all the data from devices and organize it for processing. Grouping files from different sources but related to some specific experience is a good practice. Always keep the original files untouched, duplicating those needed for processing and working only on those. Document all the processing steps, for easy replication by others. Write down all device settings used for processing, like gains or any other important settings.

Chapter 6

Conclusion

Performing a successful underwater acoustic sensor calibration experiment is a challenging task, for the equipment and facilities required, the need for measurement standards and procedures and for the whole careful organization of the experiment itself. All these various issues may have a direct impact in the result, and the precision achieved in the device calibration. This report reviews the existing procedures for hydrophone calibration, and extrapolates those to the calibration of a vector hydrophone (or vector sensor), for which there are no well established calibration procedures. Equipment requirements and characteristic are reviewed and procedures proposed, providing an interesting reading before attempting any plans for performing a calibration experiment either in tank or at sea.

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Appendices

A Calibration Logbook

Following pages contain a sample logbook, that can be used to locally record important information about the experiments. Print the needed pages and fill it during the experiments with important information related to experiment. For example, should print several copies of sensitivity files page.

- 1^{st} page contains the objectives of experiment and what data should be recorded.
- 2^{nd} page contain a schedule plan of the experiments. Each task should be filled sequentially, with the execution date and time, the estimated duration and the activity description.
- 3^{rd} page have the transducer placement for a tank experiment. Fill all the distances and device position for future reference.
- 4^{th} page have the transducer placement for an open water experiment. Fill all the distances and device position for future reference. Draw all extra sources of reflections that exist in that site and the distances between them and transducers.
- 5^{th} page show a list of the equipments used, with theirs identifications and some settings used. It have also space to fill with some signal settings.
- 6^{th} page have a diagram for draw the connections of all devices used in a tank experiment. When changing physical connections or experiment type(sensitivity or directivity), use another copy to redraw the connection diagram for later reference. Can also annotate any photo names related with the experiment.
- 7^{th} page is identical to 6^{th} one, but for an open sea experiment.
- 8^{th} and 9^{th} pages contains blank spaces to fill with information for the sensitivity and directivity experiments. Fill the header with the required information and the tables with acquisition data file names and corresponding settings used for that filename. If relevant for the experiment or known, fill the water condition field with temperatures, salinity or pressure. Any additional information, like a photo name or any relevant event occurred during experiment should be placed on notes.

All pages contain a logbook page field which must be numbered sequentially, as well as the experiment name and date for reference.

Calibration Experiment Logbook

Location: ______________________ **Date:** ______________ **Logbook Page:** ______

Performed by: ______________________________________

Description: ____

____

•Experiment objectives:

1. ____
2. ____
3. ____
4. ____
5. ____
6. ____
7. ____
8. ____
9. ____
10. ____

Experiment: ________________________ **Date:** ________________ **Logbook Page:** ______

•Daily Schedule Plan

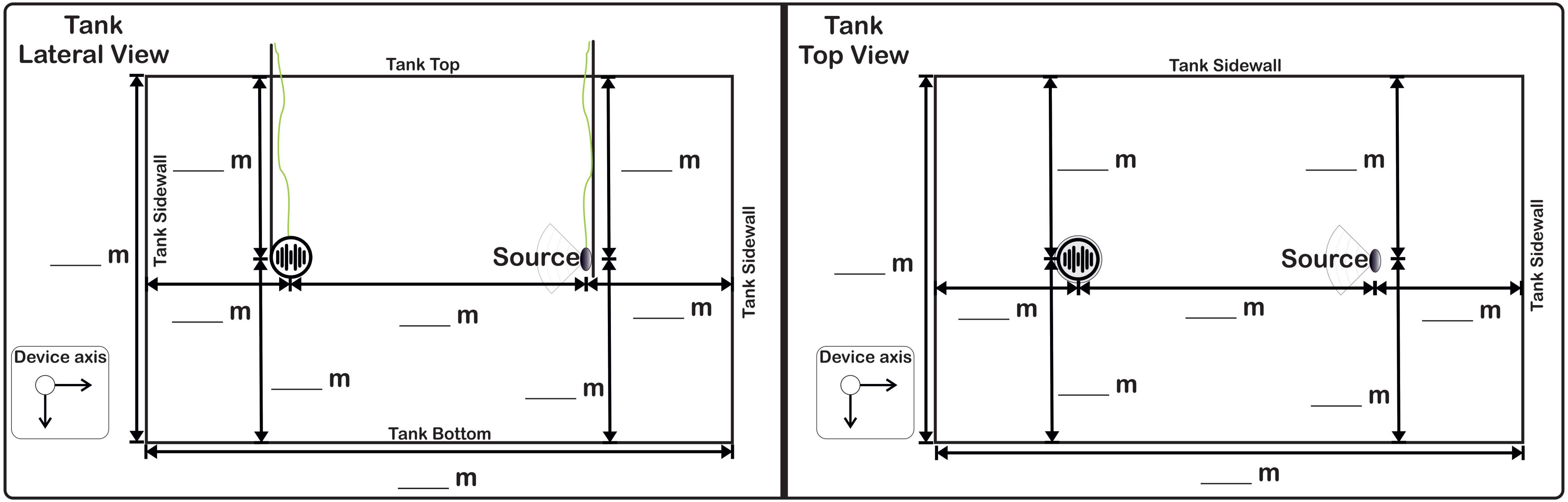
Date	Time	Duration	Activity

Experiment: ________________ Date: ________________ Logbook Page: ________

Setup # ________________ Description: ____

____

- **Tank Experiment: setup schematic, fill with tank dimensions, devices positions, respecting devices axis**

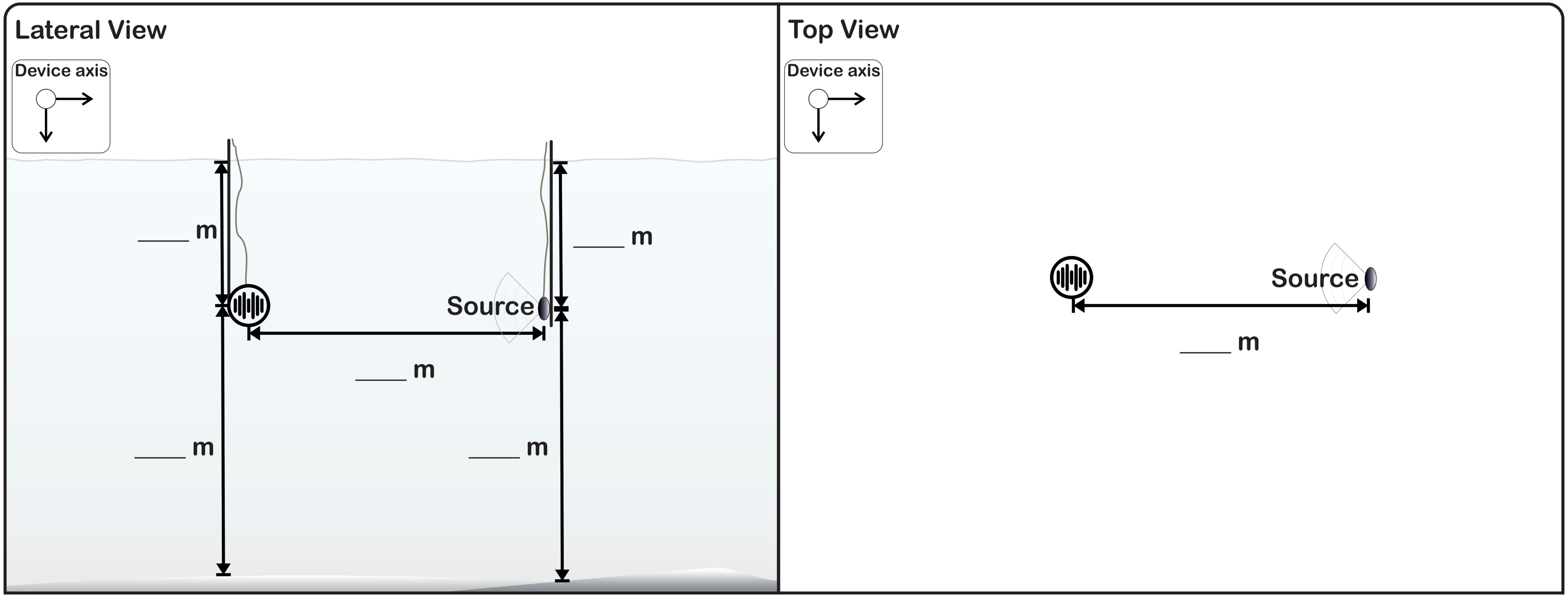


Experiment: ____ Date: ____________________ Logbook Page: ______

Setup # ________________ Description: ____

____

•**Sea Experiment: setup schematic, fill blank spaces with devices positions, respecting devices axis.** Draw any significant object to experiment, like any side wall or reflecting object. If known, record the distance from transducers to that points.



Experiment: ______________________ **Date:** ______________ **Logbook Page:** ______

Notes: ____

•Used equipment

Equipment Name	Equipment ID (Serial N., ...)	Configurations Used	Notes

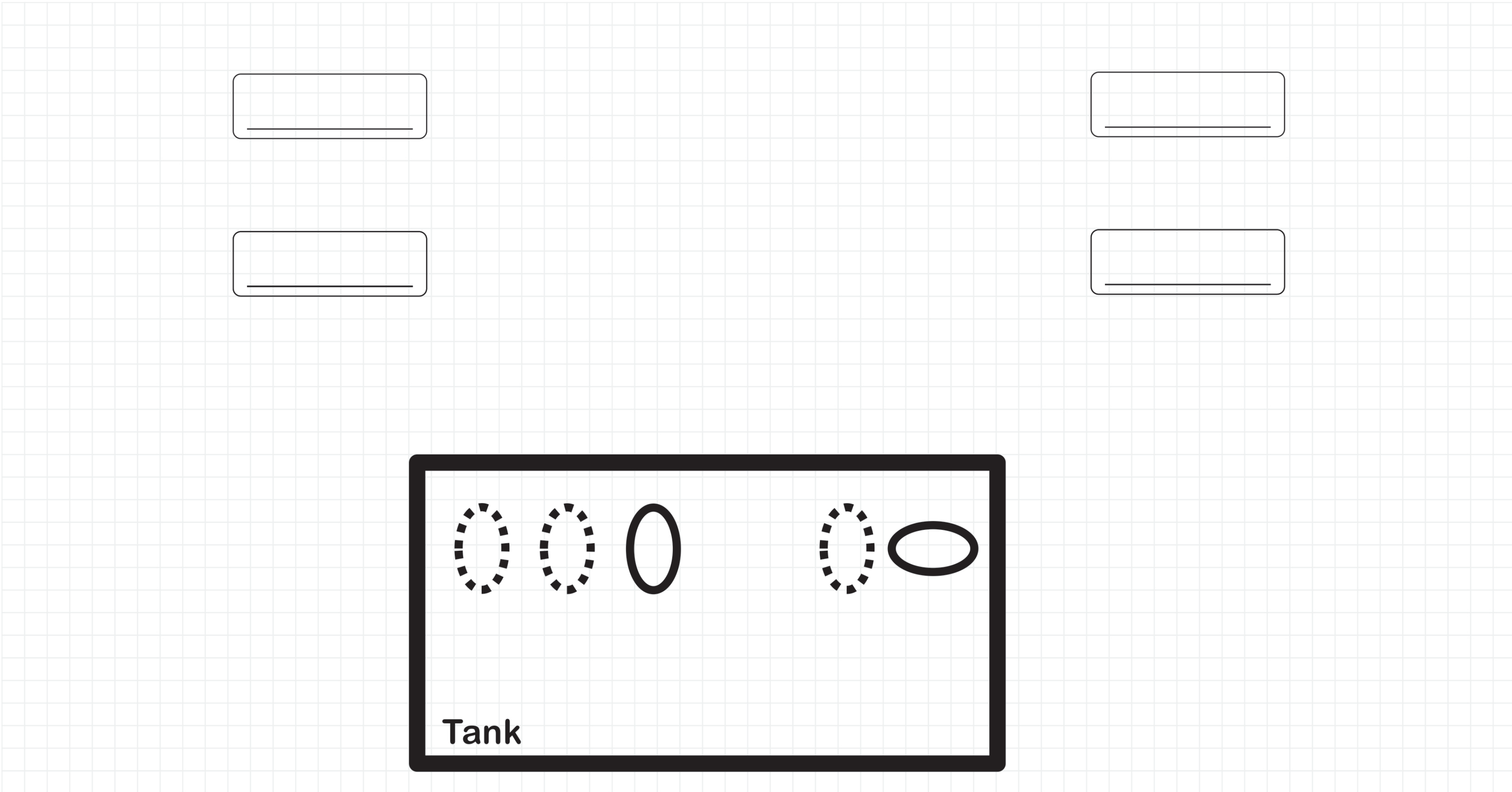
•Test signal characteristics and drive voltages

Description: ____

Signal Frequency							
Signal Voltage							
Drive Voltage							

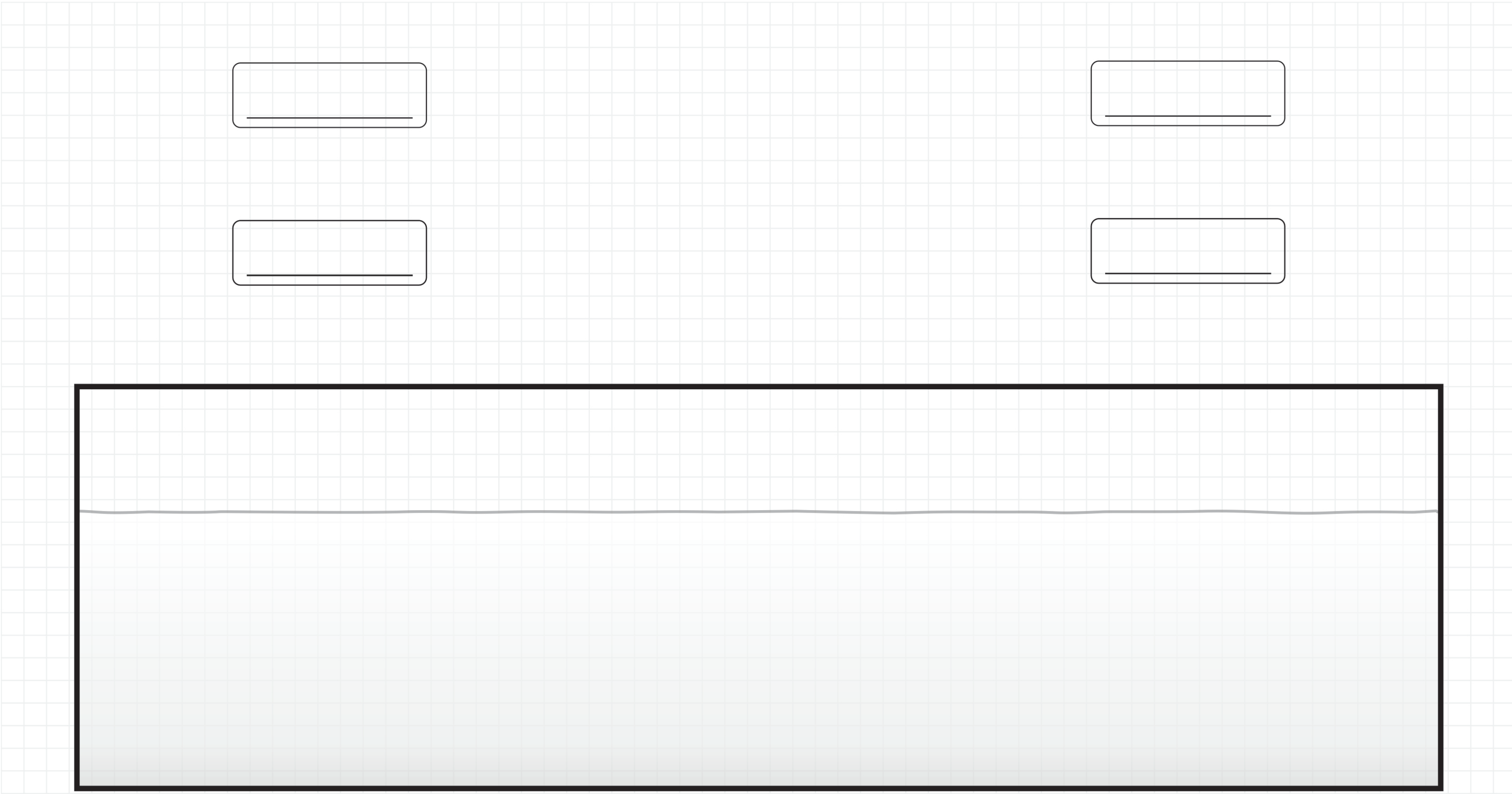
Experiment: ________________________ **Date:** ______________ **Logbook Page:** ______

•**Tank Experiment: Equipment connections diagram, draw connections between components. Identify components and add setting information (like gains, voltages,...)**



Experiment: ______________________ **Date:** ______________ **Logbook Page:** ______

•**Sea Experiment: Equipment connections diagram, draw connections between components. Identify components and add setting information (like gains, voltages,...)**



Sensitivity Experiment: ______________________ **Device:** ______________ **Axis:** ______ **Logbook Page:** ______

Date: ______ - ______- ______ **Day:** ______ **Performed by:** ______________________

Water Conditions: ______________________ **Notes:** ______________________

•Sensitivity files

Acquisition Time	WAVE Filename	Reference Filename	Freq.	Setup	Gain Settings	Pulse length /PRR	Drive Voltage	Signal Voltage	NOTES

Directivity Experiment: ______________________ **Device:** ______________ **Axis:** ______ **Logbook Page:** ______

Date: ______ - ______- ______ **Day:** ______ **Performed by:** ______________________

Water Conditions: ______________________ **Notes:** ______________________________________

•Directivity files

Acquisition Time	WAVE Filename	Freq.	Rotation Direction	Notes	Acquisition Time	WAVE Filename	Freq.	Rotation Direction	Notes