QUIETMED – Joint programme on noise (D11) for the implementation of the Second Cycle of the MSFD in the Mediterranean Sea.

quietMED

Deliverable

D3.1. Best practices guidelines on sensor calibration for underwater noise monitoring in the Mediterranean Sea

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Abstract

This document is the Deliverable “D3.1. Best practices guidelines on sensor calibration for underwater noise monitoring in the Mediterranean Sea” of the QUIETMED project funded by the DG Environment of the European Commission within the call “DG ENV/MSFD Second Cycle/2016”. The QUIETMED project aims to enhance cooperation among Member States (MS) in the Mediterranean Sea to implement the Second Cycle of the Marine Directive and in particular to assist them in the preparation of their MSFD reports by 2018 through: i) promoting a common approach at Mediterranean level to update GES and Environmental targets related to Descriptor 11 in each MS marine strategies ii) development of methodological aspects for the implementation of ambient noise monitoring programs (indicator 11.2.1) iii) development of a joint monitoring programme of impulsive noise (Indicator 11.1.1) based on a common register, including gathering and processing of available data on underwater noise.

This public document presents a review and comparison of the national implementations. It is based upon the in-depth assessment of national reports on good environmental status, environmental targets and monitoring programmes. It relies also on the update by the project partners of the work conducted so far at national levels.

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List of Abbreviations

ACCOBAMS	Permanent Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
CTN	Centro Tecnológico Naval y del Mar
EC	European Commission
ET	Environmental Targets
EU	European Union
FORTH	Foundation for Research and Technology - Hellas
IDA	In-Depth Assessment
IEO	Instituto Español de Oceanografía
IOF	Institute of Oceanography and Fisheries
ISPRA	Instituto Superiore per la Protezione e la Ricerca Ambientale
IZVRS	Inštitut za vode Republike Slovenije
MS	Member State
MSFD	Marine Strategy Framework Directive
SMART	Specific Measurable Achievable Realistic Time-bound
TGN	Technical Group on Noise
UoM	The Conservation Biology Research Group, the University of Malta
UPV	Universitat Politècnica de València

1. Introduction

The European Maritime Strategy Framework Directive 2008/56/EC requires that the Member States of the European Union achieve and maintain good Environmental Status in European waters by the year 2020 (European Commision, 2008). The operational implementation of the directive is adaptive and is reviewed every six years. It includes five main items which are:

- The assessment of marine waters state (article 8),
- The determination of the Good Environmental Status (GES, article 9),
- The establishment of Environmental Targets (ET, article 10),
- The establishment and implementation of a monitoring program (article 11),
- The establishment and implementation of a program of measures (article 13).

The directive gives a list of qualitative descriptors on which the GES is based upon. The eleventh descriptor (D11), deals with the introduction of energy in the marine environment by human activities. It states that the "*introduction, including underwater noise, must be at levels that do not adversely affect the environment*". In this regard, the MSFD recognizes underwater noise as a marine pollutant.

The compliance of the national marine strategies with the Directive requirements is formally assessed by the European Commission through a reporting process done by MS competent authorities (article 12). The results of the assessment are made available to the public. The first lessons learned from the assessment of the first cycle implementation of the MSFD are a general lack of coherence within the European Union, leading to "*as many GES as Members States*" (European Commision, 2014).

Based on the first cycle assessment, the European Commission has made recommendations with the aim to improve the level of coherency for the second cycle which starts in 2018. For this purpose, the 2008 directive has been amended (European Commision, 2017) and the 2010 decision has been revised (European Commision, 2017). Assessment and reporting guidances are also proposed for testing to members states (Walmsley, Weiss, Claussen, & Connor, 2017) (European Commision, 2017). Furthermore, the European Commission highlights the necessary reinforcement of the cooperation between Member States and the need for a better connection between national strategies and the Regional Sea Conventions strategies.

The QUIETMED Project is funded by DG Environment of the European Commission within the call "DG ENV/MSFD Second Cycle/2016". This call funds the next phase of MSFD implementation, in particular to achieve regionally coherent, coordinated and consistent updates of the determinations of GES, initial assessments and sets of environmental targets by July 2018, in accordance with Article 17 (2a and 2b), Article 5 (2) and Article 3 (5) of the Directive.

The QUIETMED project aims to enhance cooperation among Member States (MS) in the Mediterranean Sea to implement the Second Cycle of the Marine Directive and in particular to assist them in the preparation of their MSFD reports by 2018 through: i) promoting a common approach at Mediterranean level to update GES and Environmental targets related to Descriptor 11 in each MS marine strategies ii) developing the methodological aspects for the implementation of ambient noise monitoring programs (indicator 11.2.1) iii) developing a monitoring programme of impulsive noise (Indicator 11.1.1) based on a common register, including gathering and processing of available data on underwater noise. The Project has the following specific objectives:

- Achieve a common understanding and GES assessment (MSFD, Article 9) methodology (both impulsive and continuous noise) in the Mediterranean Sea;
- Develop a set of recommendations to the MSFD competent authorities for reviewing the national assessment made in 2012 (MSFD, Article 8) and the environmental targets (MSFD, Article 10) of Descriptor 11- Underwater Noise in a consistent manner taking into account the Mediterranean Sea Region approach;
- Develop a common approach to the definition of thresholds at the Mediterranean Sea level (in link with TG Noise future work and revised decision requirements) and impact indicators;
- Coordinate with the Regional Sea Convention (the Barcelona Convention) to ensure the consistency of the project with the implementation of the Ecosystem Approach Process (EcAp process);
- Promote and facilitate the coordination of underwater noise monitoring at the Mediteranean Sea level with third countries of the region (MSFD Article 6), in particular through building capacities of non-EU Countries and taking advantage of the ACCOBAMS-UNEP/MAP cooperation related to the implementation of the EcAp process on underwater noise monitoring;
- Recommend methodology for assessments of noise indicators in the Mediterranean Sea basin taking into account the criteria and methodological standards defined for Descriptor11 (Decision 2010/477/EU, its revision and guidelines).
- Establish guidelines on how to perform sensor calibration and mooring to avoid or reduce any possible mistakes for monitoring ambient noise (D11C2). These common recommendations should allow traceability in case the sensor give unexpected results and help to obtain high quality and comparable data.
- Establish guidelines on the best signal processing algorithms for the preprocessing of the data and for obtaining the ambient noise indicators;
- Implement a Joint register of impulsive noise (D11C1) and hotspot map at Mediterranean Sea Region level by impulsive noise national data gathering and joint processing.
- Enhance collaboration among a wide network of stakeholders through the dissemination of the project results, knowledge share and networking.

To achieve its objectives, the project is divided in 5 work packages which relationships are shown in Figure 1.

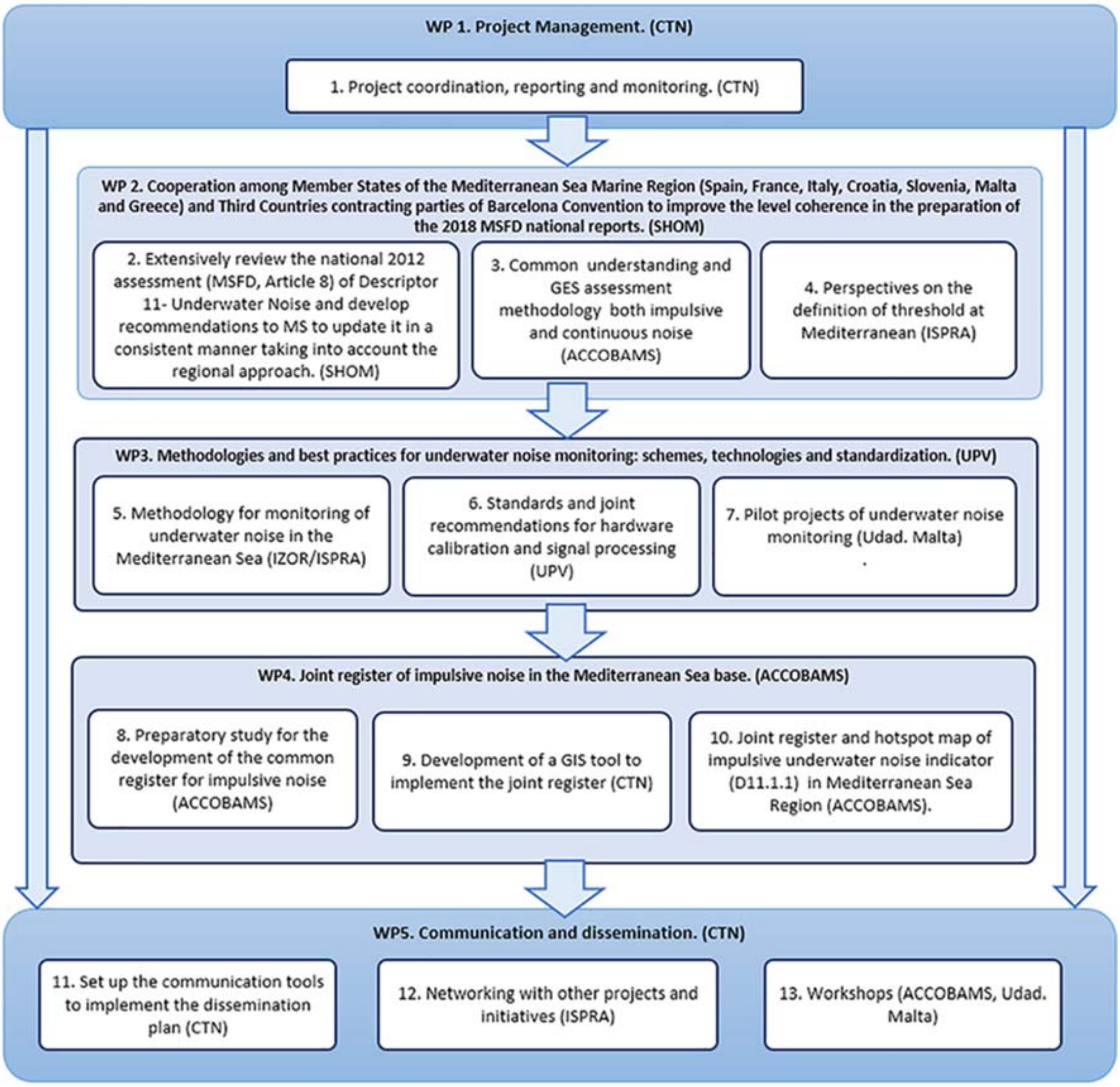

Figure 1: Work Plan Structure.

The project is developed by a consortium made up of 10 entities coordinated by CTN and it has a duration of 24 months starting on January 2017. It is important to note that the project will be carried out in close communication and collaboration with other European and regional initiatives (in particular with the TG Noise) to avoid effort duplication.

The third work package of the QUIETMED project is dedicated to Methodologies and best practices for underwater noise monitoring: schemes, technologies and standardization. Its objective is to establish guidelines on how to perform sensor calibration, mooring and signal processing in order to obtain comparable ambient noise indicators. It also intends to give guidelines on how to perform acoustic modelling and mapping in order to combine measurements and modeling/mapping as recommended by the TG-Noise. It is structured in the following actions or activities:

- Action 5 aims to provide a detailed Methodology for monitoring of underwater noise in the Mediterranean Sea using bottom mounted autonomous systems.
- Action 6 aims to give Standards and joint recommendations for hardware calibration and signal processing.
- Action 7 is the Pilot projects of underwater noise monitoring.

This report is the deliverable of the actions 5 and 6 described above. It presents a review of the different calibration techniques and standards for mooring. This review is based upon different reports and recommendations carried out in 2012 and in 2015. It relies on the in-depth assessment. It relies also on the update of the work conducted so far at national levels and it focuses on the technical implementation with the aim to improve the technical coherency in the future.

The report is organized as follows. After this introduction, the first part briefly recalls the methodology and materials used for the analysis. The second part present a comparison between the national approaches with a focus on the approaches carried out in the QUIETMED consortium member states. The main conclusions and recommendations are listed in the final part.

2. State of the art of the different joint recommendations for hardware calibration applied to bottom mounted autonomous systems.

Some previous work has been done by experts to develop standards for the calibration of hydrophones devoted to noise monitoring. The National Physical Laboratory (NPL) provides a good practice Guide No. 133 for this purpose [1]. This guide covers many different aspects and many different approaches, from vessel-based surveys and drifting systems to moored systems.

All these works emphasize that although the recorders should be supplied with full system calibration, including all the information required to determine the absolute levels of the measured data, an in-situ calibration check with a hydrophone calibrator (pistonphone) is strongly recommended. It also states that It is very risky to rely on indicative nominal calibration provided by the manufacturer at design stage, so complete calibration is recommended following the [IEC 60565 2006, ANSI S1.20 2012]. However, practical details of how to perform calibration in passive acoustic monitoring autonomous devices are not given. This is a key factor in achieving a common procedure for the calibration of these systems and at the final stage comparable noise indicator obtained using different devices by different groups. This gap is covered in the present deliverable where, among some other topics we try give recommendations for the practical calibration of Passive Acoustic Monitoring (PAM) devices taking into account their particularities, study the problem of synchronization in autonomous PAM devices when it is not possible to remotely have access to the device and give practical tips of how calibration of these devices should be done to meet all the standards.

There are national and international standards describing the calibration such as:

- IEC 60565:2006 – The calibration of hydrophones in the range 0.001 Hz to 1 MHz (available in the UK as BS 60565:2007)
- ANSI S1.20-2012 - Procedures for calibration of underwater electro-acoustic transducers.

3. About the PAM devices to calibrate

This document will describe the main guides and recommendations on the realization of the calibration of devices, taking into account not only the hydrophones (the main element) but also all the components that form the PAM devices to be calibrated.

In addition, and as to carry out any calibration is necessary a reference system (not only a referenced hydrophone) usually composed of a chain of devices where the hydrophone is the most important part, but without forgetting the amplifiers / preamplifiers, computers that store the signals and sound cards or digital analog converters that allow to condition and acquire the signal correctly.

Note that all these measurement instruments used in the referenced system will be reflected in the PAM devices to be calibrated. In most cases all of them are integrated into a Single-Board Computer that, when correctly programmed, will be able to control and modify the parameters and operation of all the components.

3.1. Elements in PAM device

Given a scenario where there are several elements that form a PAM system: such as a hydrophone (with / without amplification), electronic components that can offer attenuation or gain, an ADC controlled by a Single-Board Computer that introduce filters that can modify the sensitivity of the system.

In most cases, the ADC is embedded in the Single-Board Computer. One of the main advantages of using Single-Board Computers is that the final user or the programmer can control the behavior of its inner electronic components (i.e. gain control, embedded algorithms, design filters) through its associated software, changing the sensitivity of the Single-Board Computer. So, it is necessary to perform a calibration, not only of the hydrophone but the Single-Board Computer.

3.1.1. Hydrophone

Hydrophone is an electro acoustic transducer which, in case of passive (listening) systems, converts variations in the underwater pressure caused by underwater noise sources to the variations in electrical voltage on its output.

Typical specifications are sensitivity, frequency range (bandwidth), linearity, directivity pattern, maximum operating depth (or pressure), self-noise, operating temperature range and impedance:

Sensitivity is the rate of conversion of acoustic pressure level to electric voltage. The more sensitive hydrophone is, the more voltage it will generate from the same acoustic pressure. Sensitivity should be selected depending on the presumed noise level to be recorded. The hydrophone sensitivity is the tradeoff between good signal to noise ratio for low levels of noise and avoiding system overload with high noise levels. The recording of the quiet ambient noise (e.g. MFSD category A monitoring) would require more sensitive hydrophones than for the category B monitoring where higher levels caused by the proximity of the high level sources are expected.

Sensitivity is recommended to be in the range from –165 dB re 1 V/µPa to –185 dB re 1 V/µPa.

Frequency range is the range of frequencies in which hydrophone retains sensitivity within some tolerance levels. Frequency range should be selected depending on the presumed noise spectrum to be recorded.

Although the only mandatory frequency ranges required to satisfy the indicator 11.2.1 are the two third-octave bands with nominal center frequencies of 63 Hz and 125 Hz, it is recommended that whole system should be capable of recording higher frequencies which can be used in other professional or scientific purposes. This additional range will not add much to the cost as most of the quality hydrophones have much broader frequency range than required for the indicator 11.2.1.

Therefore, it is recommended that hydrophone frequency range should be linear from 5 Hz to 10 kHz with tolerance limits ±1 dB and linear from 5 Hz to 20 kHz with tolerance limits ±2 dB.

Directivity is the property of the hydrophone of being more sensitive in one direction then another. Hydrophone should have omnidirectional horizontal response (equal response to noise coming from all directions) over two third-octave bands (63Hz and 125 Hz) of interest. The tolerance level should not be more than ±1 dB.

Directivity pattern is dependent on hydrophone size and frequency. When size of the hydrophone becomes greater than acoustic wavelength, hydrophone will start to show directionality. With existing types of suitable hydrophones, it will typically appear at the range of tens of kilohertz. As the broader frequency range is aimed, the recommendation is that hydrophone should be omnidirectional at 20 kHz with the tolerance level of ±3 dB.

Note: If the hydrophone is placed close to the reflective structure (e.g. container of the autonomous recorder) it can cause increased directionality.

Self-noise is the noise produced by the hydrophone itself in the absence of any acoustic signal. It is normally expressed as a noise-equivalent sound pressure level in dB re1 µPa2/Hz (or 1 µPa/√Hz). The self-noise varies with acoustic frequency and as a result is usually presented as a noise spectral density level versus frequency. The self-noise is the important parameter as it represents the lowest noise level that can be recognized in the recording. However, to achieve an acceptable signal-to-noise ratio when measuring acoustic signals, the self-noise equivalent sound pressure level should be at least 6 dB below the lowest noise level to be monitored in the frequency range of interest.

It is common to compare values for self-noise with classic empirical curves for ambient noise levels in the ocean, such as those of Wenz and Knudsen. The low-noise hydrophone has been designed to optimize the noise performance, and the self-noise of such a hydrophone can approach Wenz's lowest ocean noise levels.

Having in mind that measurement is done to assess the adverse effect of the anthropogenic noise, not to assess possible biological noise minimums, the recommendation is that hydrophone self-noise levels are below 53 dB re 1 µPa2/Hz at 63 Hz and 49 dB re 1 µPa2/Hz at

125 Hz. If the hydrophone is going to be used for the measurement of underwater noise with broader frequency range of interest self-noise should be below 30 dB re 1 µPa2/Hz at 10 kHz.

Impedance is the effective resistance of the hydrophone to alternating current, arising from the combined effects of ohmic resistance and reactance. It is important in coupling the hydrophone to the cable and the front end signal conditioning electronics. Hydrophone impedance forms the frequency dependent voltage divider with input impedance of the connecting cable and the front end signal conditioning electronics. The mismatch in these two impedances can cause frequency dependent voltage loss thus decreasing useful signal to noise ratio. Most of the high quality low-noise hydrophone has been designed with internally built electronic circuits that can also provide additional voltage gain, but with low output impedance (in the range of tents of Ohm). In that way long cables and various types of front end technologies and topologies can be used without loss of the useful signal. Therefore, the use of the hydrophones with internal electronics and low output impedance is recommended.

Maximum operating depth (or pressure) and operating temperature range should be matched to the ranges expected in deployment.

The choice of the hydrophone in a PAM device is one of the most important steps when acquiring an acoustic signal. It will be necessary to obtain the calibration curve of the hydrophone in order to obtain the sound pressure of the recordings.

Usually, the manufacturer only gives the sensitivity at a certain frequency and it has to be assumed that in all the remaining frequencies the sensitivity is the same. In fact, although the manufacturer will provide the entire calibration curve of the hydrophone, it is recommended doing the calibration when the device has been purchased.

3.1.2. Measurement instrumentation.

The term Single-Board Computer is introduced to refer to any electronic development that manages to control by software all the components associated with it, such as the ADC or potentiometers of gain control.

Generally, using programmable devices like Single-Board Computers, allow the choice of a specific sampling frequency, an amplification according to the type of deployment or an equalization that allows visualizing or eliminating certain effects or sounds. Therefore, it will be necessary to perform a calibration of the Single-Board Computer to permit the acquired data can be referenced, taking into account a particular configuration programmed by the software of the Single-Board Computer.

Note that in this deliverable the term “Single-Board Computer” will be used to refer to the measuring instrumentation included in PAM device. This measurement instrumentation within the Single-Board Computer are the same as the necessaries in the referenced system. To clarify, a PAM device is a compact device that includes all the components contained in the reference system used to calibrate.

Amplifiers / preamplifiers

Either within some hydrophones as preamplifiers or as amplification within the electronics or software by means of an evaluation board. This is introduced as a gain factor (in linear or in decibels). Most of cases the amplification is invariant with the frequency.

However, is interesting to keep in mind that some hydrophones have inner preamplifiers (this is often the case for low-noise high sensitivity hydrophones). This preamplifier gain cannot usually be modified, and such hydrophones may not be appropriate for high amplitude signals. In case of preamplifiers inside the hydrophones, the gain will be included in the sensibility of the hydrophone.

Filters

In the same way as the amplification of the system is decided before doing the deployment to obtain a sensitivity according to the type of deploy category that is going to be carried out, sometimes it is necessary to design filters depending on the application. Filters are often integrated into Single-Board Computers. By default, they are designed to avoid certain problems concerning the signal processing. Specifically: the aliasing or the introduction of a high pass filter with a cutoff frequency that allows to eliminate the lowest frequencies.

Analog to Digital Converter (ADC)

The Analog to Digital Converter (ADC) is included in most of PAM devices to store data in digital domain, (i.e. digital counts) from the volts of the input. The ADC introduces by definition a quantization error that depends on the number of bits that the ADC has to perform the conversion. This translates into a scale factor. This factor must be invariant with frequency.

If in addition to the quantification error, the ADC introduces some gain or attenuation, this will be added to the gain of the whole device, leaving the scale factor only dependent on the quantization error of the converter. This can be seen in the following sections of the deliverable.

Data Storage

Data in the digital form are then stored in the memory from which can be downloaded or transmitted directly (e.g. by cable or radio) to external computer for final storage and processing.

Recordings can be continuous when system records the underwater noise throughout the entire deployment period. In order to extend deployment period which is limited by memory and battery capacity, recording can be intermittent (on-off) which means that data are recorded for some period (on) following by the standby period (off) in which the system is idle. In that way battery life and memory usage are improved thus extending deployment period available. The active and standby periods are set up in the way that all essential characteristics of the underwater noise are captured throughout deployment period.

When working with digital accounts, the maximum and minimum levels of the signal at the output of the ADC are [$-2^{nbits-1}$, $2^{nbits+1}$]. Once the signal leaves the ADC it is saved in a data audio file. The most common types of data audio files provided by PAM devices are the following:

- .WAV: digital audio format files without compression and therefore without loss. They allow to keep within their metadata information about sampling frequency, quantization bits, etc.

  They will be files with data within the range [$-2^{nbits-1}$, $2^{nbits+1}$]. However, if they are read by Matlab / R / Octave with the audioread or wavread instruction, they will take into account the quantization (reading the file metadata) and return values between [-1,1] corresponding to volts. It should be noted that this range does not mean that there are values that reach their maximum, this will only happen when clipping is existing.

- .DAT, files without raw format, and therefore, without loss. These files do not contain any metadata information and, at the time of reading them, it is necessary to format them, knowing how they have been recorded by the ADC. They will be signals within the range [$-2^{nbits-1}$, $2^{nbits+1}$]. It should be noted that this range does not mean that there are values that reach their maximum, this will only happen when clipping is existing.

Section 4.3 explains how to calibrate the Single-Board Computer of a PAM.

4. Practical recommendations for the calibration of PAM devices.

Calibration of the PAM devices need to be done in water and in air. This is a widespread practice for hydrophone calibration since at low frequencies (25 Hz - 315 Hz) sensitivity of a hydrophone is the same in air as in water [2,3]. Following this idea, classical methodology for hydrophone calibration using comparison techniques has been adapted for the calibration of the whole PAM system.

It is recommended to carry out the calibration of a device at regular intervals of time (every year) to ensure the initial system settings given by the provider have not wandered.

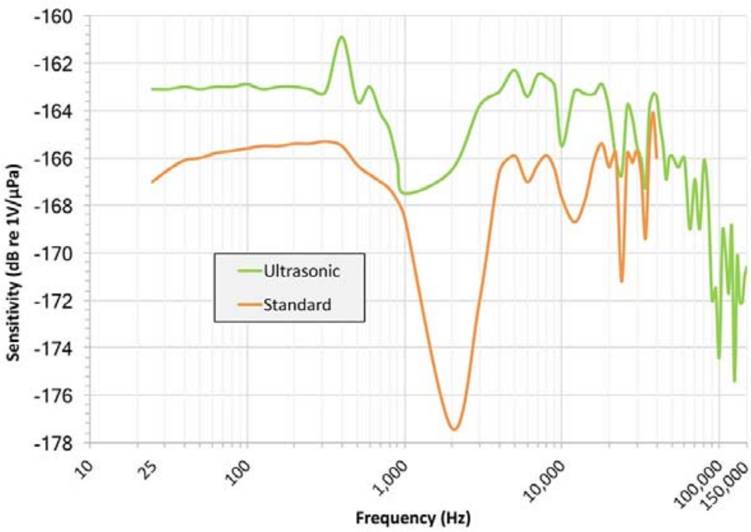

Figure 2: Example of sensitivity of 2 different hydrophones along the frequency domain [4].

Figure 2 shows an example of the sensitivity curve of a hydrophone [4], where at 1KHz it is -168 dB re 1V / µPa and at 1.25KHz it is -178 dB re 1V / µPa, a difference of almost 10 dB (orange curve). This is a good example to see that it cannot be assumed that a hydrophone is invariant with frequency. So, it is necessary to perform the calibration if the manufacturer does not give a curve like the one in Figure 2. In this case the error when supposing it will be 10 dB.

4.1. Considerations about the sensitivity in referenced system before doing a calibration.

Ideally, the sensitivity of the whole system should be chosen to be an appropriate value for the amplitude of the sound being measured. The aim in the choice of 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.

Thus, for measurement of low amplitude signals (for example, ambient noise in a quiet location), a high sensitivity system is preferable. However, for measuring high amplitude signals (for example, at close range to a source of high output level), a lower sensitivity is preferable to avoid saturation in the signals recorded [5].

It is difficult to choose the sensitivity of the measuring system without some advance knowledge of the amplitude of sound emitted likely to be measured. To build in some flexibility, it is desirable to design the electronics by means a programmable Single-Board Computer in the PAM system to be calibrated or by controlling the measurement instrumentation (usually changing the gain of the amplifier) corresponding to the referenced system.

It is necessary to clarify that hydrophones or microphones using as reference system (knowing its sensitivity and other parameters) don't work by itself as a referenced system in a calibration. Together with them is needed measuring instrumentation as an analogue digital acquisition system, a computer to capture, manage and analyse the signals emitted, and an amplifier (or preamplifier incorporated in the hydrophone / microphone) that allows to choose the gain needed to adapt the sensitivity of the reference equipment to capture the signals emitted avoiding saturation or a poor signal to noise ratio.

The use of a microphone to a sound level meter is preferred, since the values emitted by the sound level meters are expressed in 1/3 octave bands, and therefore, the noise around the frequency of interest can interfere in the Measurement of the SPL. The use of the parameters available by some sound level meters, as time weighting (Fast - Slow) or frequency weighting (A - C), will allow us to avoid these possible interferences.

There are also sound level meters that allow unprocessed audio recordings, which can be accessed later through a computer. Once the recordings are made on the computer, it will be easy to use or design adhoc filters to avoid possible interferences within the 1/3 octave.

4.2. Sensitivity basics.

Sensitivity (sh) is described in terms of the electrical voltage developed per pascal of acoustic pressure and is stated in units of V/Pa (or, using units more appropriate for a typical sensitivity magnitude, in 1µV/Pa). The sensitivity level is often expressed in decibels (dB re 1V/µPa). Note that the choice of a 1V/µPa as the reference value leads to hydrophone sensitivity levels having very large negative values, for example

$$56\left[\frac{1\mu V}{Pa}\right] = 56 * \frac{10^{-6}[1V]}{10^{-6}[1\mu Pa]} = 56 * 10^{-12}\left[\frac{1V}{\mu Pa}\right] \quad (1)$$

and taking logarithms:

$$20 * log10(56 * 10^{-12})\left[dB\ re\frac{1V}{\mu Pa}\right] = -205\left[dB\ re\frac{1V}{\mu Pa}\right] \quad (2)$$

Eq. (3), (4) and (5) define voltage (v), pressure (p) and sensitivity (sh) in dB referred to 1V, 1µPa and 1V/µPa. These are the main 3 concepts in every calibration.

$$v[dB\ re\ 1V] = 20 * log10\left(\frac{v'[V]}{1V}\right)[dB\ re\ 1V] \quad (3)$$

$$SPL\ [dB\ re\ 1\mu Pa] = p[dB\ re\ 1\mu Pa] = 20 * log10\left(\frac{p[Pa]}{1\mu Pa}\right)[dB\ re\ 1\mu Pa] \quad (4)$$

$$sh\left[dB\ re\frac{1V}{\mu Pa}\right] = 20 * log10\left(sh\left[\frac{1V}{\mu Pa}\right]\right)\left[dB\ re\frac{1V}{\mu Pa}\right] \quad (5)$$

In fact, sensitivity is defined by the following equation:

$$SPL\ [dB\ re\ 1\mu\text{Pa}] = p[dB\ re\ 1\mu\text{Pa}] = v[dB\ re\ 1V] - sh\left[dB\ re\frac{1V}{\mu Pa}\right] \quad (6)$$

It is important to point that when taking logarithms working on voltage or pressure $(20 * log10)$ is different than in power $(10 * log10)$.

In case of water, ref is 1µPa and in air is 20µPa. In order to obtain SPL [dB re 20µPa] from SPL [dB re 1µPa], Eq. (7) and (8) were applied:

$$p[20\mu Pa] = \frac{p[1\mu Pa]}{20} \quad (7)$$

$$\begin{aligned} SPL\ [dB\ re\ 20\mu Pa] = p[dB\ re\ 20\mu Pa] &= 20 * log10(p[20\mu Pa]) = \\ &= 20 * log10\left(\frac{p[1\mu Pa]}{20}\right) = \\ &= 20 * log10(p[1\mu Pa]) - 20 * log10(20)[dB] = \\ &= p[dB\ re\ 1\mu Pa] - 20 * log10(20)[dB] = \\ &= p[dB\ re\ 1\mu Pa] - 26.02[dB] \end{aligned} \quad (8)$$

4.3. Calibration of the Single-Board Computer

This requires a signal generator, an audio interface, the Single-Board Computer to be calibrated, an oscilloscope and a computer capable of acquiring the sinusoidal tone burst introduced in the Single-Board Computer. Figure 3 shows an outline of the realization:

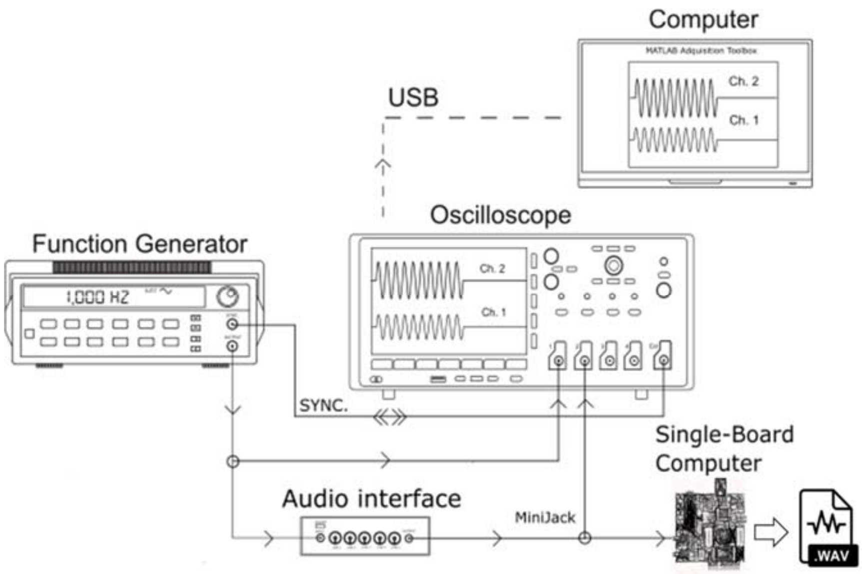

Figure 3. Layout of the set up in the calibration of the Single-Board Computer.

In detail, it can be seen how a miniJack-miniJack cable connects from the output of the audio interface to the Single-Board Computer and the oscilloscope, where the signal will be displayed. It is necessary that the miniJack cable can be connected to the audio input of the Single-Board Computer in order to calibrate it. In this realization, by means Matlab's Acquisition Toolbox installed at the computer connected to the oscilloscope, the signals seen on the oscilloscope are recorded. The utilization of Matlab´s Acqusition Toolbox is optional, most of oscilloscopes provide dedicated software to acquire the signals and its configuration into a computer.

In the oscilloscope (and in the computer) two different channels will be displayed:

- Channel 1: signal emitted by the function generator (sinusoidal burst signal) is displayed. Signal discarded.
- Channel 2: signal at the output of the audio interface (input of the Single-Board Computer) is displayed in the oscilloscope and store in the computer. This signal is well conditioned thanks to the audio interface and will correspond to $\boldsymbol{v}$ (see Figure 4).

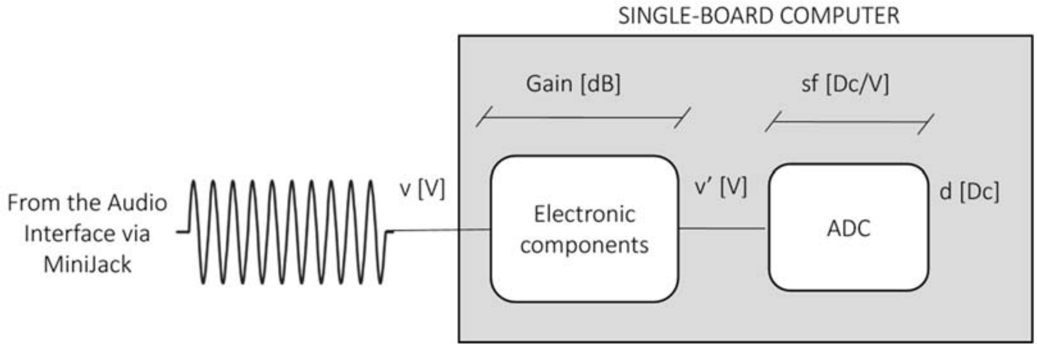

Figure 4: Block diagram related to the components within the Single-Board Computer.

The Single-Board Computer will generate a .wav / .dat file where the signals will be stored once having passed through all the components of the Single-Board Computer, including the ADC. These stored data correspond to d (see Figure 4).

Table 1 shows general notation in order to define equations and concepts in

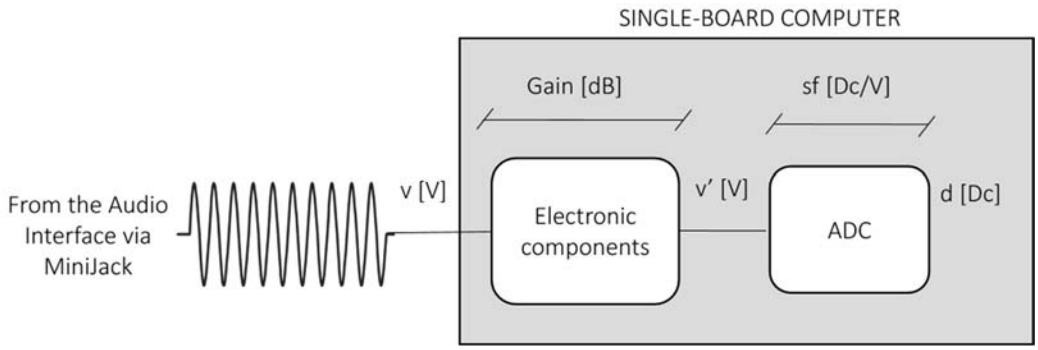
SINGLE-BOARD COMPUTER
Gain [dB]
sf [Dc/V]
From the Audio Interface via MiniJack
v [V]
Electronic components
v' [V]
ADC
d [Dc]

Figure 4 as well as resume definitions used in the document. The following equations shows the relationships between them.

Table 1. General notations

PAM	Passive Acoustic Monitoring
ADC	Analog to Digital Converter
sf [Dc/V]	Scale factor
d [Dc]	Digital counts
v' [V]	Voltage before the ADC in Volts
v [V]	Voltage delivered by the hydrophone in Volts

$$v'[V] = \frac{d[Dc]}{sf[\frac{Dc}{V}]} \qquad \text{where } sf = 2^{nbits-1} \qquad (9)$$

It is possible to obtain the volts at the input of the ADC v' by means Eq. (9). It can be seen that the scale factor (sf) is defined as the relationship between the digital accounts provided by the files generated by the Single-Board Computer and the volts v'.

Therefore, it is possible to figure out the gain ($Gain_{measured}$) of the electronic components of the Single-Board Computer by means of the v (signal in oscilloscope) and the v' obtained from

d [Dc] (signal in the file .wav/.dat generated by the Single-Board Computer). See Eq. (10) and (11).

$$Gain_{measured} = \frac{v'[V]}{v[V]} \quad (10)$$

$$Gain_{measured} = \frac{d[Dc]}{sf\left[\frac{Dc}{V}\right] * v[V]} \quad (11)$$

And taking logarithms of Eq. (10):

$$Gain_{measured}[dB] = v'[dB\ re\ 1V] - v\ [dB\ re\ 1V] \quad (12)$$

This calculated gain ($Gain_{measured}$) should be the same that the provider set up in the configuration of the device ($Gain_{provided}$). If there is any difference between both, a correction factor (cf_{gain}) will be defined to perform that discrepancy (see Eq. (13) and (14)).

$$cf_{gain} = \frac{Gain_{measured}}{Gain_{provided}} \quad (13)$$

$$cf_{gain}[dB] = Gain_{measured}[dB] - Gain_{provided}[dB] \quad (14)$$

4.4. Calibration of the hydrophone

To perform the calibration, a hydrophone or a reference sound level meter will be necessary to tell us the Sound Pressure Level (SPL) [dB re 1µPa] we have in a certain position, the same position where the PAM system to be calibrated will be located. The following diagram in Figure 5 will be used which shows all the elements involved in the data acquisition of a PAM system.

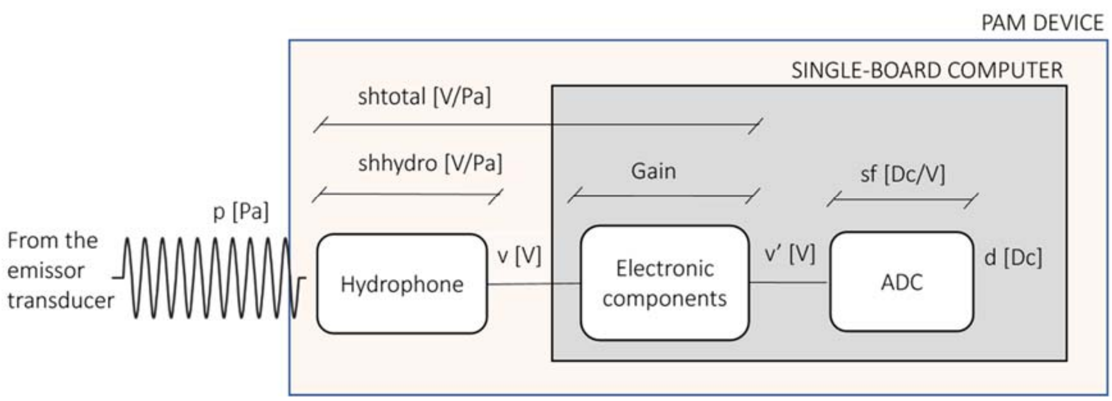

Figure 5: Block diagram related to a PAM device.

Figure 5 summarize any PAM device (included the referenced ones). Also, Table 2 is provided to introduce the parameters used for each of the devices. For example, in the reference device, digital counts (d) in the files generated by the Single-Board Computer will be defined by a subscript R (d_R). In the device to be calibrated, the volts in the input of the ADC (v') will be defined by a subscript X (v'_X)

Table 2. Particular notations

sf_R [Dc/V]	Scale factor in the reference device
sf_X [Dc/V]	Scale factor in the device to calibrate
d_R [Dc]	Digital counts in the reference device
d_X [Dc]	Digital counts in the device to calibrate
v'_R [V]	Voltage before the ADC in the reference device. In Volts
v'_X [V]	Voltage before the ADC in the device to calibrate. In Volts
v_R [V]	Voltage delivered by the hydrophone in the reference device. In Volts
v_X [V]	Voltage delivered by the hydrophone in the device to calibrate. In Volts
p [µPa]	Pressure in microPascals in input of both systems, the reference device and device to calibrate.
shhydro [V/µPa]	Hydrophone sensitivity of the hydrophone. In V/µPa
sh_Rhydro [V/µPa]	Hydrophone sensitivity of the hydrophone in the reference device. In V/µPa
sh_Xhydro [V/µPa]	Hydrophone sensitivity of the hydrophone in the device to calibrate. In V/µPa
shtotal [V/µPa]	Total sensitivity. In V/µPa
sh_Rtotal [V/µPa]	Total sensitivity in the reference device. In V/µPa
sh_Xtotal [V/µPa]	Total sensitivity in the device to calibrate. In V/Pa

$$p\ [\mu Pa] = \frac{v\ [V]}{shhydro[\frac{V}{\mu Pa}]} \tag{15}$$

$$v\ [V] = \frac{v'\ [V]}{Gain} \tag{16}$$

$$p\ [\mu Pa] = \frac{v'[V]}{shhydro\left[\frac{V}{\mu Pa}\right] * Gain} = \frac{v'[V]}{shtotal\left[\frac{V}{\mu Pa}\right]} \tag{17}$$

where $$shtotal\left[\frac{V}{\mu Pa}\right] = shhydro\left[\frac{V}{\mu Pa}\right] * Gain$$

The sensibility $shhydro$ is defined as the quotient between the volts that the hydrophone throws at its output divided by the pressure p that enters through the transducer, being its units [V/Pa]. It is possible to obtain the pressure from the volts and vice versa (see Eq. (15)) with $shhydro$.

On the other hand, the parameter $Gain$ (see Eq. (16)) is a dimensionless factor that relates the volts at the output of the hydrophone (v) with those of the ADC input (v'). To summarize, in Eq. (17) is defined the whole system from the sound pressure level in the hydrophone input.

Taking logarithms in Eq. (15), (16) and (17):

$$p\ [dB\ re\ 1\mu Pa] = v\ [dB\ re\ 1V] - shhydro\left[dB\ re\ \frac{1V}{\mu Pa}\right] \tag{18}$$

$$v\,[dB\ re\ 1V] = v'\,[dB\ re\ 1V] - Gain[dB] \tag{19}$$

$$\begin{aligned} p\,[dB\ re\ 1\mu Pa] &= v'[dB\ re\ 1V] - shhydro\left[dB\ re\ \frac{1V}{\mu Pa}\right] - Gain[dB] = \\ &= v'[V] - \left(shhydro\left[dB\ re\ \frac{1V}{\mu Pa}\right] + Gain[dB]\right) = \\ &= v'[dB\ re\ 1V] - shtotal\left[dB\ re\ \frac{1V}{\mu Pa}\right] \end{aligned} \tag{20}$$

where $$shtotal\left[dB\ re\ \frac{1V}{\mu Pa}\right] = shhydro\left[dB\ re\ \frac{1V}{\mu Pa}\right] + Gain[dB]$$

It is necessary to emphasize that the sound pressure level of the emitted signal is captured in both devices (reference device, also formed by a hydrophone, an amplifier and an ADC) and in the device to be calibrated) will be the same, since they must be located in the same position.

From the digital accounts d_R obtained in the reference device, the acoustic pressure of the signal at the input of the reference device will be calculated ($nbitsR$, sf_R, $Gain_R$ and $sh_R hydro$ are known) (see Eq. (21) and (22)).

$$v'_R[V] = \frac{d_R[Dc]}{sf_R[\frac{Dc}{V}]} \qquad \text{where } sf_R = 2^{nbitsR-1} \tag{21}$$

$$p\,[dB\ re\ 1\mu Pa] = v'_R[dB\ re\ 1V] - sh_R hydro\left[dB\ re\ \frac{1V}{\mu Pa}\right] - Gain_R[dB] \tag{22}$$

According to the information provided from the device to calibrate, the calculation of the sensitivity will be different:

a) If the info provided about the device to calibrate is just $nbitsX$, v'_X will be calculated (see Eq. (23)). Then, $sh_X total$ will be obtained and defined as $sh_X total_{measured}$.

$$v'_X[V] = \frac{d_X[Dc]}{sf_X[\frac{Dc}{V}]} \qquad \text{where } sf_X = 2^{nbits-1} \tag{23}$$

$$sh_X total_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] = v'_X[dB\ re\ 1V] - p[dB\ re\ 1\mu Pa] \tag{24}$$

b) If the info provided about the device to calibrate is $nbitsX$, and $Gain_{Xmeasured}$ has been calculated previously (see Eq. (11)), it will be easy to obtain the volts v_X (i.e. input of the Single-Board Computer) and find out $sh_X hydro$ (defined as $sh_X hydro_{measured}$) (see Eq. (27)).

$$v'_X[V] = \frac{d_X[Dc]}{sf_X[\frac{Dc}{V}]} \qquad \text{where } sf_X = 2^{nbitsX-1} \tag{25}$$

$$v_X\ [dB\ re\ 1V] = v'_X\ [dB\ re\ 1V] - Gain_{Xmeasured}[dB] \tag{26}$$

$$sh_X hydro_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] = v_X[dB\ re\ 1V] - p\ [dB\ re\ 1\mu Pa] \tag{27}$$

$$cf_{hydro} = sh_X hydro_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] - sh_X hydro_{provided}\left[dB\ re\ \frac{1V}{\mu Pa}\right] \tag{28}$$

Once $sh_X hydro_{measured}$ has been calculated it will be possible to check if it conforms to the $sh_X hydro$ provided by the manufacturer defined as $sh_X hydro_{provided}$.

c) If the info provided about the device to calibrate is $nbitsX$ and $Gain_{Xprovided}$, and $Gain_{Xmeasured}$ has not been calculated, the possible correction factor obtained once the calibration of the Single-Board Computer has been carried out will be reflected in $sh_X hydro_{measured}$. Therefore, the comparison between $sh_X hydro_{measured}$ and $sh_X hydro_{provided}$ will not be a comparison between real sensitivities of hydrophones.

$$v'_X[V] = \frac{d_X[Dc]}{sf_X[\frac{Dc}{V}]} \qquad \text{where } sf_X = 2^{nbits-1} \tag{29}$$

$$v_X\ [dB\ re\ 1V] = v'_X\ [dB\ re\ 1V] - Gain_{xprovided}[dB] \tag{30}$$

$$sh_X hydro_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] = v_X[dB\ re\ 1V] - p\ [dB\ re\ 1\mu Pa] \tag{31}$$

$$cf_{total} = sh_X hydro_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] - sh_X hydro_{provided}\left[dB\ re\ \frac{1V}{\mu Pa}\right] \tag{32}$$

$$cf_{total} = cf_{hydro} + cf_{gain} \tag{33}$$

Table 3 shows a summary of the parameters that must be obtained in the calibration of the sensitivity of a PAM device. It is verified that $sh_X total_{measured}$ can be obtained as the following Eq. (34):

$$sh_X total_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] = sh_X hydro_{measured}\left[dB\ re\ \frac{1V}{\mu Pa}\right] + Gain_{Xmeasured}[dB] \tag{34}$$

Table 3. Example of PAM devices parameters

PAM device	$sh_X hydro_{measured}$	$Gain_{Xmeasured}$	$sh_X total_{measured}$
RTSYS	-154 dB re 1V/uPa @ 63 Hz	10 dB	-144 dB re 1V/uPa @ 63 Hz

	-157 dB re 1V/uPa @ 125 Hz -160 dB re 1V/uPa @ 2 kHz		-147 dB re 1V/uPa @ 125 Hz -150 dB re 1V/uPa @ 2 kHz
SAMARUC	-160 dB re 1V/uPa @ 63 Hz -162 dB re 1V/uPa @ 125 Hz -162 dB re 1V/uPa @ 2 kHz	30 dB	-130 dB re 1V/uPa @ 63 Hz -132 dB re 1V/uPa @ 125 Hz -132 dB re 1V/uPa @ 2 kHz
UL1	-162 dB re 1V/uPa @ 63 Hz -162 dB re 1V/uPa @ 125 Hz -164 dB re 1V/uPa @ 2 kHz	12 dB	-150 dB re 1V/uPa @ 63 Hz -150 dB re 1V/uPa @ 125 Hz -152 dB re 1V/uPa @ 2 kHz

Depending on the available information in the device to calibrate it will be possible to obtain $sh_X hydro_{measured}$, $Gain_{Xmeasured}$ and $sh_X total_{measured}$. Also, it is needed to calculate these parameters at each frequency to obtain a curve along the frequency domain.

Both in the RTSYS devices and in the SAMARUC, the manufacturer gives us the theoretical value of the sensitivity of the hydrophone, in addition to telling us what is the gain that applies to its electronics included in the Single-Board Computers.

Table 4. Parameters provided by PAM devices

PAM device	$sh_X hydro_{provided}$	$Gain_{Xprovided}$	$sh_X total_{provided}$
RTSYS	-165 dB re 1V/uPa @ 1 kHz	15.3 dB	-150 dB re 1V/uPa @ 1 kHz
SAMARUC	-167 dB re 1V/uPa @ 1 kHz (-187 re 1V/uPa @ 1kHz + 20 dB preamplifier)	30 dB	-137 dB re 1V/uPa @ 1 kHz

In the calibrations that will be carried out for the QUIETMED, the sensitivity curves of the entire PAM device (including the gain) will be obtained.

5. Applying guidelines methods for calibration in air.

General guidelines will be given to perform the calibration of any PAM device. This methodology will be applied in the commercial devices used in QUIETMED:

- RTSYS. https://rtsys.eu/en/underwater-acoustic-recorders/
- SAMARUC. http://samaruc.webs.upv.es

The corresponding calibrations have been carried out with reference devices that have the same way of acquiring signals, although in many cases the measuring instruments are controlled by a computer.

Air calibration needs to be done in an anechoic chamber with an omnidirectional sound source [2]. The frequencies to be measured in air are in the range of the 1/3-octave central band frequencies: 50, 63, 80, 100, 125, 160, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 3150 Hz.

All signals need to be recorded simultaneously by all devices (parallel mode). This can be a problem in some autonomous PAM devices that do not allow external synchronization. For those devices that do not allow any wired or wireless connection that triggers the recording of the device, continuous recording mode should be employed, and it will be necessary to process and analyze the audio to separate it into each one of the signals emitted.

In addition to the calibrations made with the commercial devices, another calibration was performed, specifically the UL1 device developed by the IACM-FORTH. This calibration was carried out in the facilities of the Laboratory of Underwater Acoustic Measurements of IACM-FORTH and the results obtained were compared and corroborated by conducting a similar experiment at sea. For more information about this calibration, consult the document QUIETMED_WD_Greece_North1_pilot_project_report.pdf. As a summary, UL1 (device to be calibrated) and TC4032 (referenced system) were placed, hanged from a tube, at 1m distance from a speaker acting as a source. Therefore, the calibration was done simultaneously in the two devices.

5.1. Calibration in Gandia (UPV) Anechoic Chamber.

For the QUIETMED pilot project the anechoic chamber located in the Universitat Politècnica de València - EPSG and a commercial dodecahedron loudspeaker (12-speaker omnidirectional OmniPowerTM Type 4292-L) was employed. The sound source should be placed in the middle of the anechoic chamber to help the uniform and omnidirectional distribution of the sound (see Figure 6). The PAM devices and reference hydrophones should be in the far field of the source (distance *D*) and all at the same distance from the sound source (see again Figure 6). Care must also be taken so that PAM devices and reference hydrophones are place at the same height. The PAM and referenced systems where placed vertically.

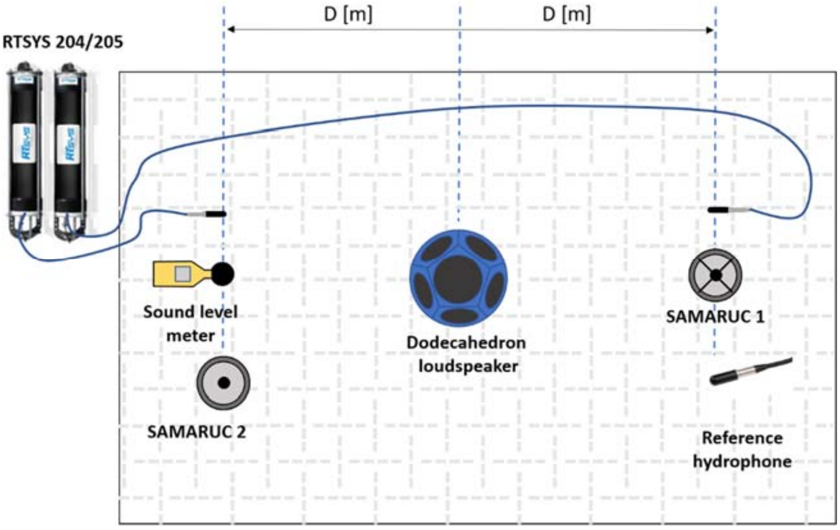

Figure 6: Layout of the elements for the calibration in the anechoic chamber.

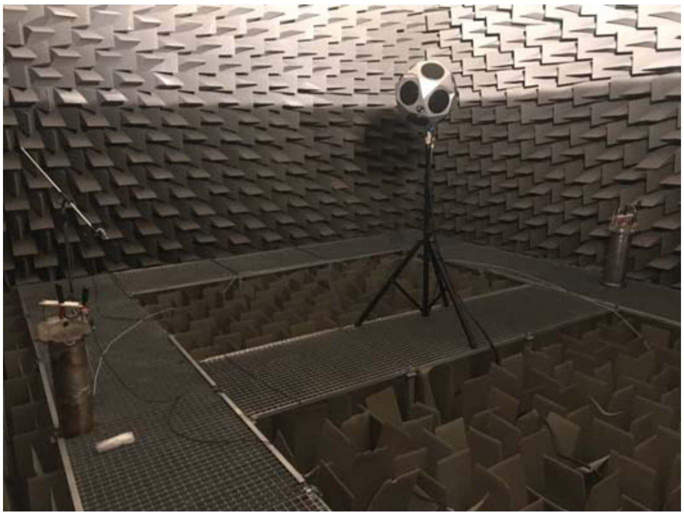

Figure 7: Practical layout for simultaneous calibration of 4 PAM devices in the QUIETMED project.

Table 4 shows the measurement instrumentation used in this calibration task.

Table 5. Measurement instrumentation used in Gandia anechoic chamber

	Measurement instrumentation	
Source and signal generation	Loudspeaker	12-speaker omnidirectional OmniPowerTM Type 4292-L
	Sound Card	Bruel & Kjaer omnipower 4292
	Amplifier	Bruel & Kjaer omnipower 4292
	Signal generator	Bruel & Kjaer omnipower 4292
Referenced System 1	Amplifier	Brüel & Kjær 4189
	Acquisition	Brüel & Kjær 4189
	Storage	Brüel & Kjær 4189
	Hydrophone / Microphone / Sound Level Meter	Brüel & Kjær 4189
Referenced System 2	Amplifier	Sound Amplifier B&K Nexus
	Acquisition	Sound Card Zoom UAC-2
	Storage	Computer
	Hydrophone / Microphone / Sound Level Meter	Brüel & Kjær 4189
Referenced System 3	Pystonphone	Sound calibrator B&K 4231

The sound source needs to be driven by a sinusoidal tone burst of duration 10 seconds (approx.). It is recommendable to repeat this process for different sound source amplitudes to estimate the dynamic range of the PAM device at different frequencies. A preliminary swept in amplitude for a fixed frequency is recommended to have an approximate idea of the where the sound is below sensitivity and where saturates the PAM device. To avoid the number of measurements becoming very large, limited number of amplitude steps should be used. We have employed 9 different sound source amplitudes.

5.1.1. Results

Note that throughout this experiment there was an important electrical interference of 50 Hz coming from outside of the anechoic chamber. Due to the fact that its intensity level was higher than some of the signals emitted, some harmonics appeared conditioning the calibration work. This sound is present in all the acquired signals, both in the reference systems and in the PAM devices since a calibration was performed simultaneously or in parallel mode (i.e. all the devices placed in the anechoic chamber at the same time and the omnidirectional loudspeaker emitting just once)

Since the source of this sound will be external (it is not located at the same distance from all the devices) it may have affected each of the devices differently, reaching each of them with different levels. This will be one of the reasons why the sensitivity obtained has a large variance along the frequencies. Figure 8 shows the sensitivity obtained in anechoic chamber in Gandia (UPV).

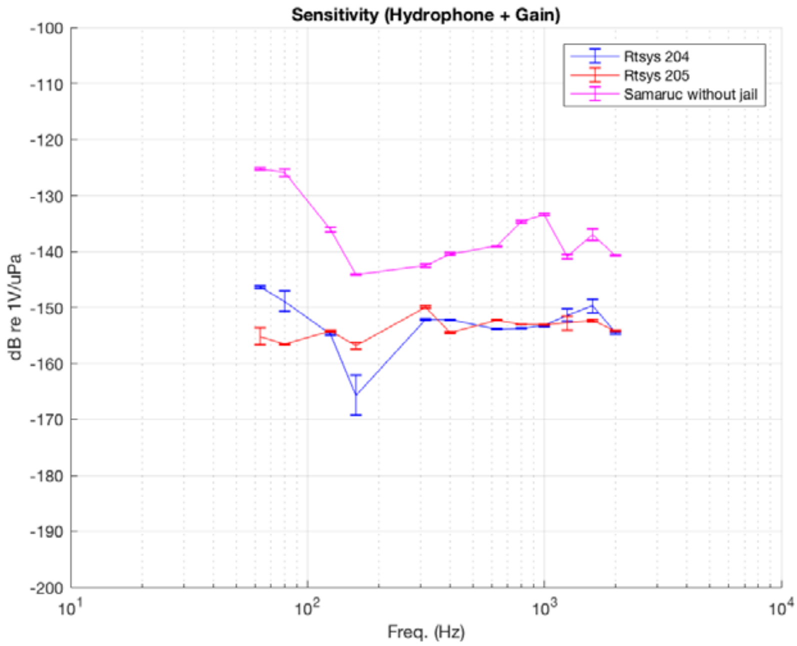

Figure 8: Sensitivity of the 3 devices to calibrate.

In this calibration task, gain from integrated preamplifier (in RTSYS and SAMARUC) has not taken into account, so that, measured sensitivity will consist of hydrophone sensitivity and integrated pre-amplifier gain.

Indeed, the calibration curves are not flat as they should, but it seems that they are around the sensitivity the manufacturer provides (only a value centered in 1kHz) for all the frequencies. Is necessary to take into account the geometry used when making calibration simultaneously mode and not with substitution of the devices (as did in CTN water tank).

In summary, the sensitivity curves obtained should be centered along the -150 dB in the RTSYS devices and in the -137 dB in the SAMARUC device (see Table 4). However, it is verified how the measurements made in the anechoic chamber are not as expected. This can be due to the simultaneous realization of the calibration (with the devices located in different places) as well as the external electrical noise.

6. Applying guidelines methods for calibration in water.

Calibration in water of PAM devices should be done in an analogous manner we made in air, i.e. by comparison with the calibrated hydrophone. The distance of the PAM device to the sound projector should be chosen so that the delay of the reflected signal is greater than the burst length (see Appendix A).

Devices were calibrated in a water tank at the CTN facilities (3150Hz-10kHz), taking into account that the devices are positioned at the same point and the measurements are made replacing one device with another.

We have performed an additional calibration at same frequencies in a water tank at the UPV (Gandia) that does not follow in some parts (such as free field or absence of reflections) the recommendation of the IEC 60565 standard [2]. Assuming this, we will use measurements in the reverberant field to check if this affects something or not the calibration. In the Gandia tank, measurements were made in parallel mode and therefore with only one emission of the signals. The limitations obtained by this method will be shown.

6.1. Centro Tecnológico Naval y del Mar water tank.

Measurements are carried out as follows:

a. Projector TC4040 and reference hydrophone are attached to the georeferenced positioners. Both hydrophones are aligned first at the loading zone.
b. Both hydrophones are placed at their positions as it is described in Figure 10.
c. 0 degrees at the horizontal plane is found acoustically.
d. Reference measurements are carried out.
e. Reference hydrophone is removed and A1. sensor is placed ensuring that both acoustic centers are placed at the same position.
f. Measurements are carried out sweeping in frequency. Once one frequency is tested, A1.1. is rotated by 10 degree and measurements are repeated.

The whole process is repeated 3 different times. Each time the whole process is repeated including the total removal of the hydrophones from the water tank and electrical connections are set again. Hydrophones are cleaned and wetted properly before any measurement set.

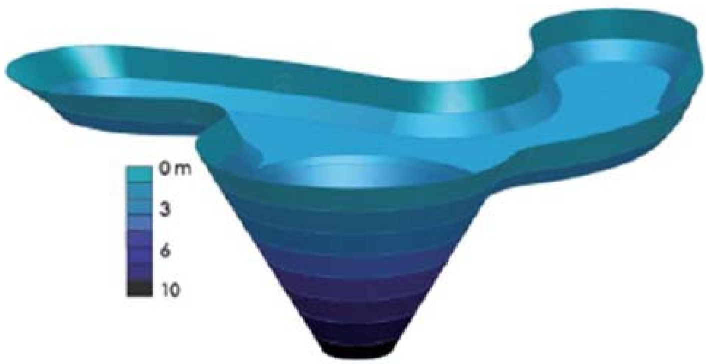

Figure 9: 3D model of the tronco-conical tank facility at CTN.

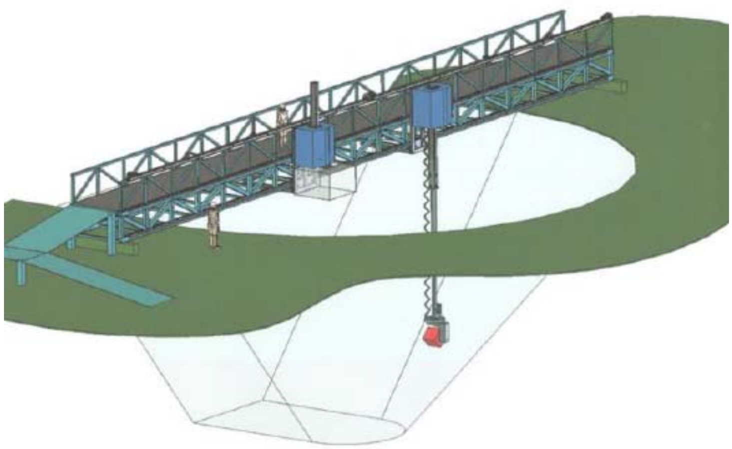

Figure 10: 3D model of the tronco-conical tank with rig showing one system under test at CTN.

Table 6 shows the measurement instrumentation used for the calibration carried out.

Table 6. Measurement instrumentation used in CTN water tank

	Measurement instrumentation	
Source and signal generation	Loudspeaker	Reference Projector *Reson* TC4040
	Sound Card	Data Acquisition Module. *National instruments.* NI – PXIe – 1073/6124
	Amplifier	Sound Amplifier Reson EC60 – 70
	Signal generator	Computer
Referenced System 1	Amplifier	RF and Ultrasonics Power Amplifier *Electronics & Innovation* 1040 L
	Acquisition	Data Acquisition Module. *National instruments.* NI – PXIe – 1073/6124
	Storage	Computer
	Hydrophone / Microphone / Sound Level Meter	Reference Hydrophone *Reson* TC4033
Referenced System 2	Pistonphone	Pistonphone *G.R.A.S.* 42AA class 1
	Coupler	RA 0078 coupler

We employed the reference hydrophone to register the entire process and to translate the voltage it detects into a pressure value at this position [2,3,6]. In a second step the reference hydrophone was replaced first with the SAMARUC PAM device (with and without hydrophone jail) and second, with the RTSYS device with the aid of the automatic positioning system.

Before and after each time the reference hydrophone TC4033 is placed and removed from the water, its sensitivity at 250 Hz is checked by means of the use of a pistonphone type 42AA. This is done in order to check for possible changes in the sensitivity of the reference hydrophone.

6.1.1. Results.

The sampling frequency of SAMARUC system was set to 24 kHz. and the RTSYS device was set to 96 KHz., both configurations with a sample rate greater than 20 kHz, which allows to emit signals of 10KHz as maximum frequency. In case of RTSYS calibration has been performed up to 48 KHz.

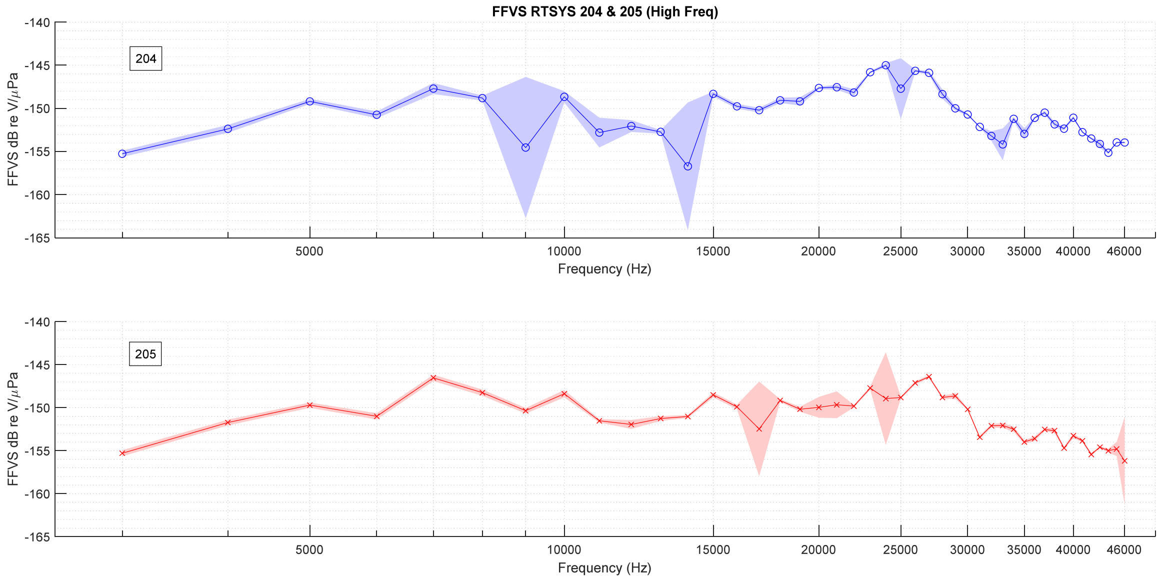

Figure 11: Sensitivity of RTSYS Devices.

The sensitivity curves obtained (Figure 11 and 12) show results that are close to those provided by the manufacturers, given the curves move close to the theoretical sensitivity.

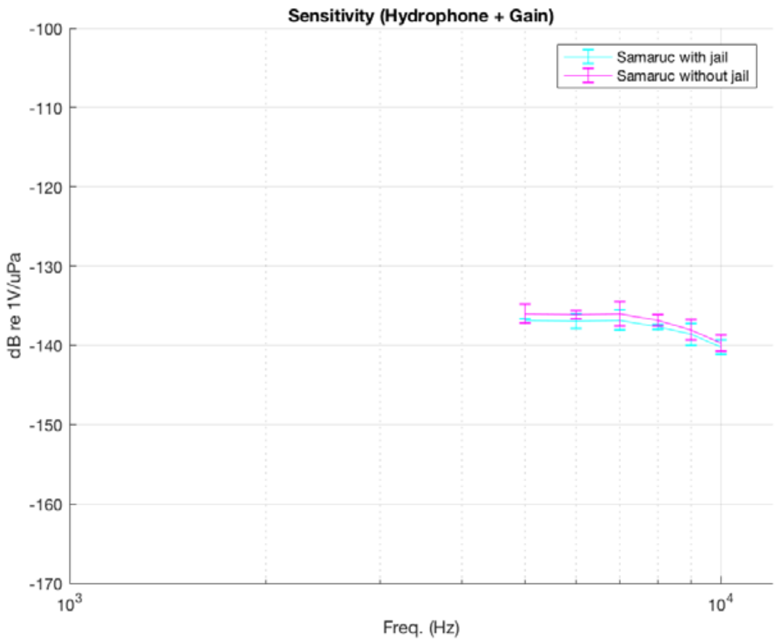

Figure 12: Sensitivity of SAMARUC PAM device with and without jail.

In Figure 12 it can be seen difference between the SAMARUC device with or without que protection cage of its hydrophone. Sensitivity of the device decreases when the cage is used. Note that in Cabrera´s Pilot Project, the device was deployed without it.

6.2. Campus de Gandia (UPV) water tank.

We have performed an additional calibration in a water tank at the UPV (Gandia) that does not follow in some parts (such us free field or absence of reflections) the recommendation of the IEC 60565 standard. The reason we did it that way was, among others, the lack of time due to the strong urge to have the system in Malta for the deployment. However, we think that the results obtained in this calibration may be of interest [3,6]. We can use these measurements, for instance, to obtain the sensitivity of the systems and compare with the results given with the previous calibration in CTN following the IEC standards.

This comparison may serve to have some idea of the effect of how some variables as water tank dimensions, calibrating in a reverberating field, and simultaneous calibration (i.e. parallel mode) affect the final result. All these measurements were used to compare different calibration techniques and we think they may merit some interest for anyone trying to understand the influence in all these variables in the final calibration procedure. That´s the main reason we would like to include some of these results in the deliverable.

Table 7. Measurement instrumentation used in Gandia water tank

	Measurement instrumentation	
Source and signal generation	Loudspeaker	Underwater loudspeaker
	Sound Card	Red Pitaya
	Amplifier	Red Pitaya
	Signal generator	Personal computer
Referenced System 1	Amplifier	Brüel & Kjær Nexus
	Adquisition	Red pitaya
	Storage	Computer
	Hydrophone / Microphone / Sound Level Meter	Brüel & Kjær 8103D

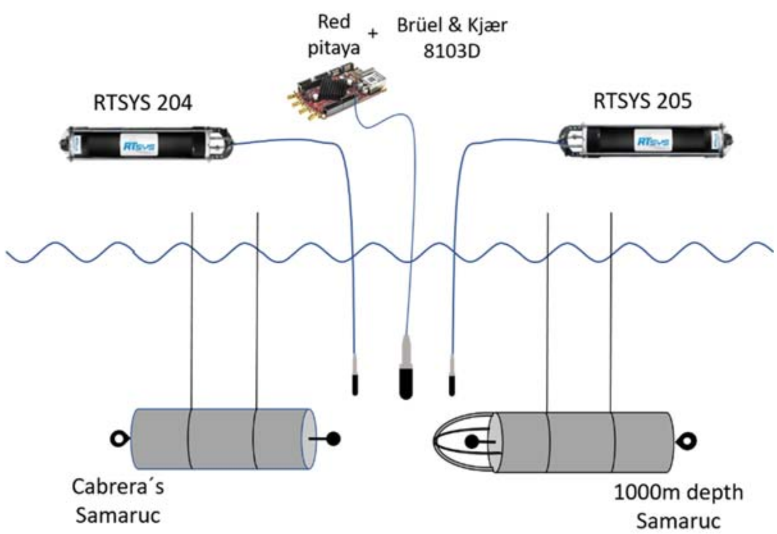

Figure 13: Layout for simultaneous calibration of 4 PAM devices in the QUIETMED project. View from the emitter transducer.

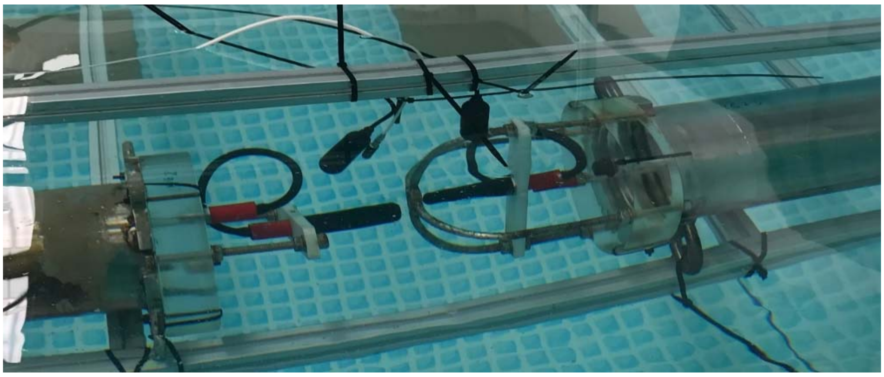

Figure 14: Detail of the placement of the 4 PAM devices to calibrate and the referenced one.

Water calibration was accomplished in a tank of dimensions 10x5x1.5 m^3. The water tank had an automatic positioning system to place the elements always at the same distance. Before water calibration of RTSYS and SAMARUC, the entire system was calibrated using reference hydrophone Brüel & Kjær 8103D (see Figure 13 and 14). For that purpose, two experiments have been done:

1) 25-cycle sinusoidal burst
2) 7500-cycle sinusoidal burst

both generated in the PC and sent to the audio amplifier using the Red Pitaya. So, this process was repeated twice changing the frequency of the burst from 2 kHz up to 10 kHz and then changing the amplitude of the signals emitted.

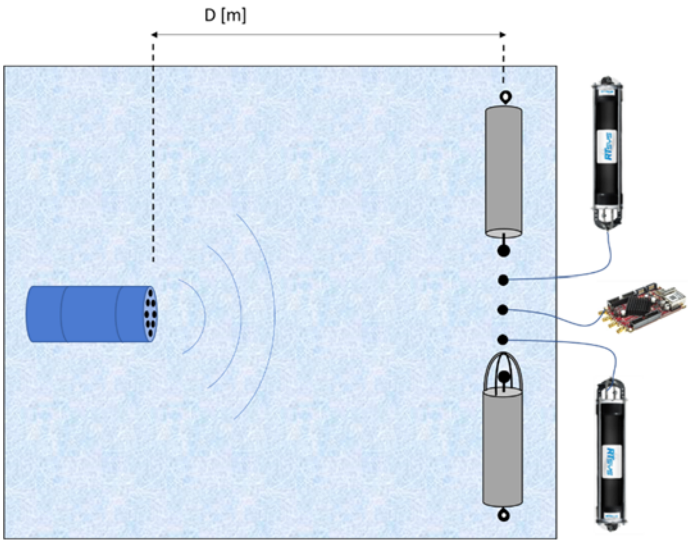

Figure 15: Layout for simultaneous calibration of 4 PAM devices in the QUIETMED project. Top view.

6.2.1. Results

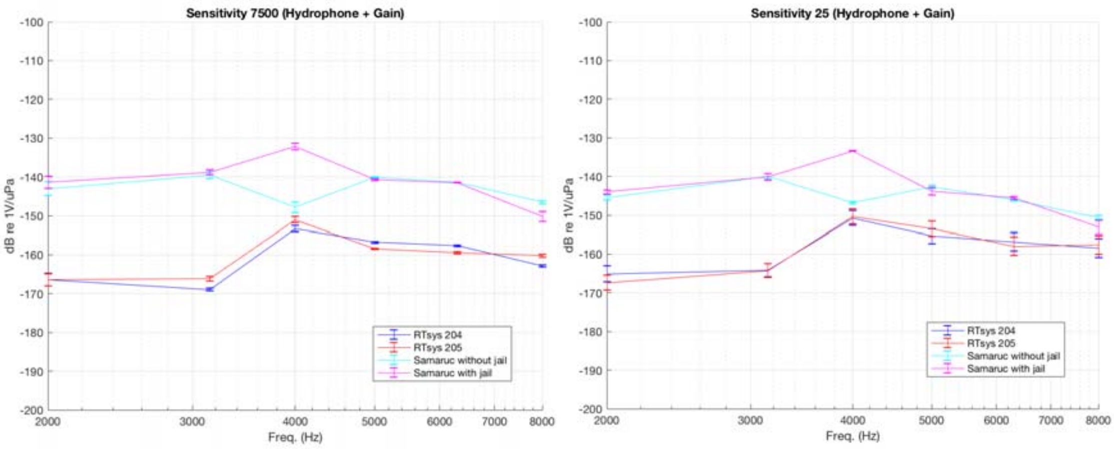

Figure 16: Sensitivity of 4 devices with a) 7500 cycles signals and b) with 25 cycles signals.

The results obtained in the reverberant field (7500 cycles each signal) are shown in Figure 16a. With fewer cycles (25), without a reverberant field, results are shown in Figure 16b.

We can verify how the influence of the geometry or location of the devices when making a calibration is important, given that the sensitivity does not behave as a straight line but has a lot of variation throughout of the frequency. There will be a part of this variance due to the housing of the devices, but it is not the only reason why curves are obtained in this way.

So, sensitivity obtained below 4000 Hz is not consistent. It is important to remember this calibration task is made simultaneously in all of devices and although each device is located very close to the others, the echoes produced by its walls will affect differently depending on the placement. This effect may be due to the small dimensions of the water tank.

Focusing on the curves of the SAMARUC device of both experiments (magenta and light blue curves), it can be seen a difference of around 15 dB over 4000 Hz. Since it only occurs at this particular frequency, it may be due to the fact that the position of the cage has caused that either the direct signal or some echo has contributed to this difference. The distance between the cage and the hydrophone is in fact comparable to the wavelength of a 4000 Hz signal.

The results are not consistent with those obtained in the CTN water tank, both in the sensitivities of the SAMARUCs and in the RTSYS. The effect is lower in the RTSYS from the frequency of 4000 Hz because the hydrophones of these devices were almost in the same position as the reference hydrophone.

Anyway, it is considered that doing the calibration simultaneously implies that the devices are not placed in the same location, and the echoes arrive in different ways to each, so that the sensitivities obtained cannot serve as calibration.

It is recalled that the effect of performing the calibration simultaneously is reduced when all the devices are placed inside an anechoic chamber (in air in this deliverable) where echoes are avoided in the walls.

Summarizing, the sensitivity curves obtained show different behavior than expected. The simultaneous realization of the calibration and the dimensions of the water tank are the possible causes of these results.

7. APPENDIX A: Free Field Sensitivity Measurements

7.1. Separation Distance

Larger dimensions of hydrophones used for the calibration are:

Table 8. Sensitive area of hydrophones

Hydrophone	Larger dimension (sensitive area) mm
TC4033	25
TC4040	53
HTI-99	33

Therefore, minimum distances can be seen in Figure 17, to ensure an uncertainty smaller than 0.2 dB [2]. These calculations have been made using a factor of 2.

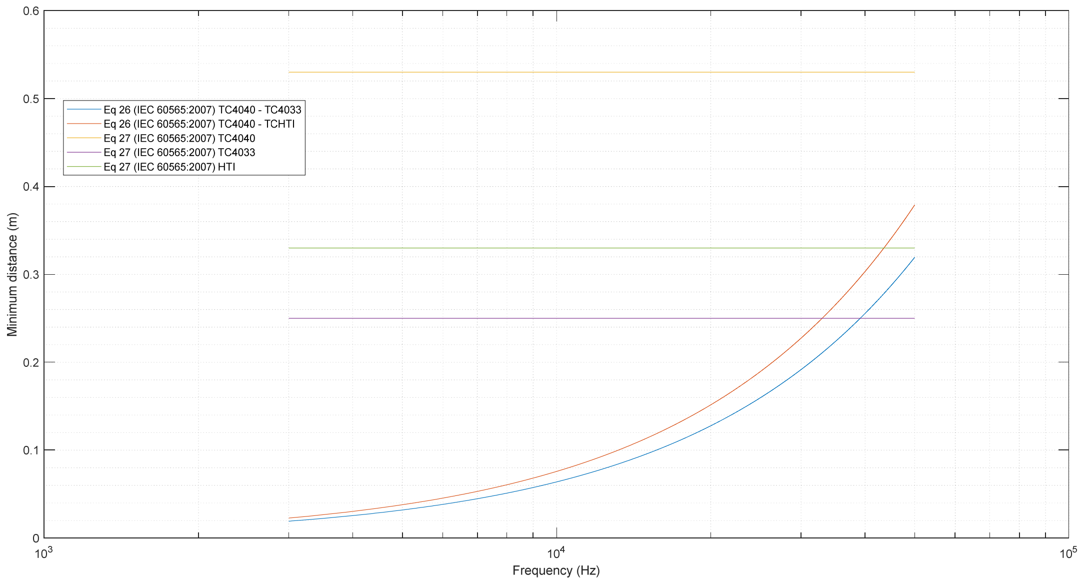

Figure 17. Minimum Distance from TC4040 to Reference hydrophones TC4033 and HTI-99.

As it can be seen in Figure 17, minimum distance is somewhat less than 0.6 meters. It is worth to mention that an approximation of the speed of sound in water is used (c = 1400 m/s). Therefore, to maximize the delay between the direct path and early reflections 0.6 meters will be chosen as the separation distance.

7.2. Echo-free time computation

To establish the length of the stimuli, the echo-free time defined as the time from the arrival time of the sound and the arrival time of the early reflections. The echo free time is the amount of time available for analysis and will limit the number of cycles that can be sent per each frequency.

There are some considerations that need to be taken into account on the Gandia (UPV) water tank dimensions according to IEC 60565:2006 [2].

Assume that the tank dimensions are *Lxwxh* (Length x Width x Height), and projector (underwater speaker) and hydrophone are *d* apart.

The transmitting part (largely due to projector) has some bandwidth, hence Q factor in the time domain. It will take Q signal periods within a pulse to reach steady amplitude. The pulse duration will be: $\tau = Q/f_{low}$ where τ is pulse duration and f_{low} is the lower limit of the frequency range required.

On the other hand, pulse should be short enough in order not to allow reflections to overlap with direct sound. This set limitations to pulse duration.

For the reflection between transducers: $\tau \leq 2\,d/c$, where c is the speed of the sound in the water
From the back wall reflection: $\tau \leq (L-d)/c$
From the surface reflection: $\tau \leq \left(\sqrt{h^2+d^2}-d\right)/c$
Assuming $Q = 2$ which is low.

f_{low}	$2kHz$	$3kHz$	$4kHz$
τ	1e-3	0.66e-3	0.5e-3
d	0.75 [meters]	0.5 [meters]	0.375 [meters]
L	2.25 [meters]	1.5 [meters]	1.125 [meters]
h	2 [meters]	1.4 [meters]	1 [meters]

Results of the computation of the echo-free time are shown in Table 9 according the dimensions and geometry of the CTN water tank (see Figure 18).

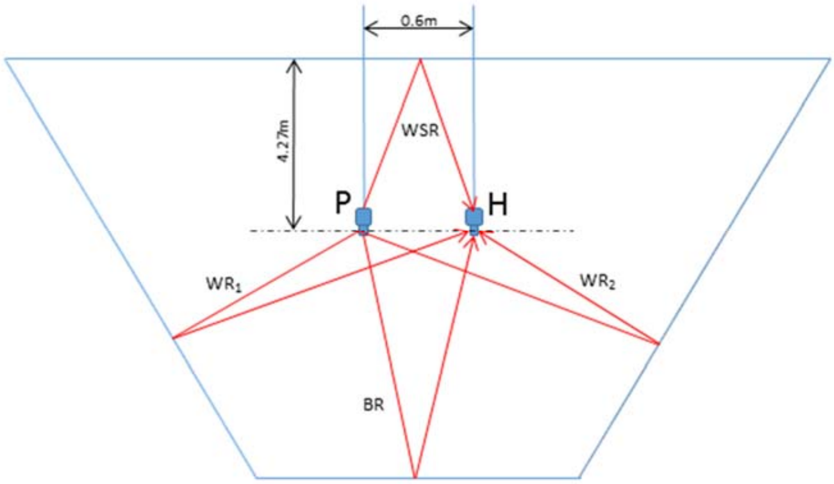

Figure 18. Scheme of direct path and early reflections from walls and water surface.

As it can be seen in Table 9, the minimum difference between the direct path time of arrival and the first reflections is T_n = 5.97 ms. Therefore, this is the echo-free time that will be available for analysis, in order to be on the safe side, a pulse duration (τ) of 5 ms is proposed.

Table 9. Direct Path and Early reflections times of arrival

Reflection	Time of arrival (s)	Time of arrival – Direct Path = Tn (s)
Direct Path	4.29 e-4	0.00
WR1	6.40 e-3	5.97 e-3
WR2	6.40 e-3	5.97 e-3
BR	6.80 e-3	6.37 e-3
WSR	7.60 e-3	7.17 e-3

The number of cycles that can be transmitted within this gate using burst techniques is frequency dependent and can be seen in Figure 19.

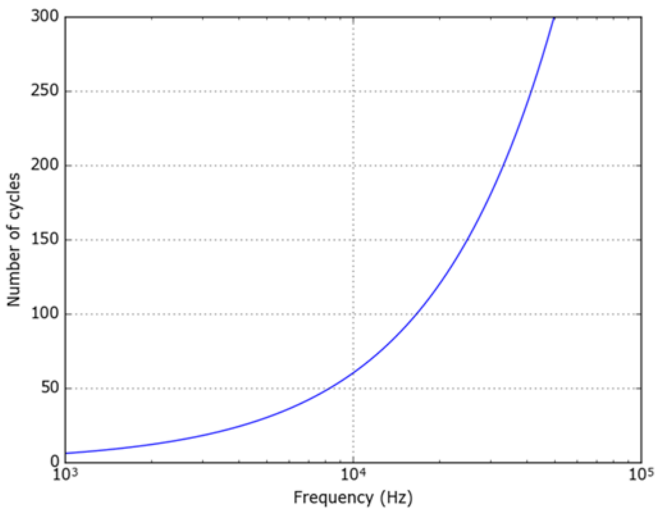

Figure 19. Number of cycles within the burst signal with 5.97 ms of echo-free time per frequency.

As it can be seen in Figure 19, for 5 kHz, the number of cycles is 25. Depending on the Q factor of the projector, this number of cycles can be enough to be able enough accuracy when computing the sound energy within the burst signal received.

The Q factor of a hydrophone/transducer is defined in this context, as the number of cycles of a certain frequency for the transducer to reach a steady-state of reception/emission. For the reference hydrophone TC4040 and the reference projector TC4033 this Q factor is 2.

7.3. Pulse duration

As it has been computed before, the pulse duration (τ) is proposed to be 5 milliseconds. This pulse duration should satisfy the following equations according to clause 2.6 of IEC 60565:2006 [2]:

Table 10. Requirements of clause 2.6 of IEC 60565:2006.

IEC 60565: 2006 Clause 2.65 Requirements		
$\tau < T_n$	5 ms < 5.97 ms	5 e-3 < 5.97 e-3
$\tau > Q/f$	5 ms > 2/1000 ms	5 e-3 > 2 e-3
$\tau < d/c$	5 ms < 0.6/1400 ms	5 e-3 < 4.28 e-3
$\tau > 2/W$	5 ms > 2/50 e3 ms	5 e-3 > 4 e-5

Where:

- T_n = echo-free time
- Q = Q factor
- f = frequency
- d = distance between hydrophones
- c = speed of sound
- W = overall bandwidth of the whole measurement system takin into account the transducers

7.4. Pulse repetition

The pulse repetition will be set to 0.25 seconds. This time is large enough so that the energy of the pulse transmitted has died out.

8. Bibliography

[1] National Physical Laboratory. M, "*Good practice Guide for Underwater Noise Measurements*" Guide Number 133.
[2] European Standard. EN 60565 "*Underwater acoustics – hydrophones – Calibration in the frecuency range 0.01 Hz to 1 MHz". IEC 60565:2006*
[3] ANSI S1.20-2012 – "*Procedures for calibration of underwater electro-acoustic transducers"*.
[4] *https://www.wildlifeacoustics.com/support/documentation*
[5] R. P. A. Dekeling et al., "*Monitoring guidance for underwater noise in European seas: a guidance document within the common implementation strategy for the Marine Strategy Framework Directive"*. Part I, Part I,. Luxembourg: Publications Office, 2014.
[6] Betke, K et al., "*BIAS Standards for Noise measurements*". Aims, Processes and Recommendations. Amended." Verfuß U.K., Sigray P., 2015.