JUMP

Joint Action: a stepping-stone for underwater noise monitoring in Portuguese water

Deliverable 3.1- State-of-the-art review of monitoring practices for background noise

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1 EXECUTIVE SUMARY

This review presents best practices guidelines for measuring and monitoring underwater noise to meet the Marine Strategy Framework Directive (MSFD) requirements. Throughout this deliverable, different types of noise measurement equipment, various methodologies and systems for obtaining acoustical data, data processing, and appropriate metrics for reporting noise levels are discussed. The recommended methodologies are described for both continuous and impulsive noise monitoring to ensure adequate data collection for policy making and conservation management.

Regulatory requirements reflect the increasing need to monitor underwater noise due to the growing pressure of anthropogenic activities in the ocean and their risk to sea life. The present recommendations highlight the best practices and identify some uncertainties and ambiguities of noise measurement as well as their solutions.

In addition, a number of projects involving monitoring underwater noise in Europe and contributing to the fulfilment of the MFSD requirements are also discussed.

SUMÁRIO EXECUTIVO

Este documento apresenta recomendações das melhores práticas de medição e monitorização do ruído submarino para o cumprimento dos requisitos da Diretiva Quadro Estratégia Marinha (DQEM). Ao longo deste relatório, são discutidos diferentes tipos de equipamento de medição de ruído, várias metodologias e sistemas de obtenção de dados acústicos, o processamento dos dados e as métricas apropriadas para apresentar os níveis de ruído. As metodologias recomendadas são descritas tanto para a monitorização do ruído contínuo como para a monitorização do ruído impulsivo, para assegurar a recolha de dados adequados para as decisões políticas e para a gestão da conservação.

Os requisitos regulamentares refletem a necessidade crescente de monitorizar o ruído subaquático devido ao aumento da pressão das atividades antropogénicas no oceano e ao seu risco para a vida marinha. As recomendações apresentadas evidenciam as melhores práticas e identificam algumas incertezas e ambiguidades da medição do ruído, bem como as suas soluções.

Adicionalmente, são também abordados vários projetos que envolvem a monitorização do ruído submarino na Europa e que contribuem para o cumprimento dos requisitos da DQEM.

2 INTRODUCTION

Sound sources in the marine environment can be of natural (physical or biological) and of anthropogenic origin. The physical processes that contribute to the underwater sound are for example, the waves, wind, currents, precipitation, turbulence, and underwater volcanoes eruptions (Hildebrand, 2005). Sound sources of biotic origin are produced, for example, by marine mammals, fishes, invertebrates, and other marine animals. These sounds are fundamental for navigation, communication, avoiding predators, detection of prey and finding mates (Peng et al., 2015).

Anthropogenic sounds result from human activities in the ocean such as recreation, shipping, research, exploitation of resources and can be generated both non-intentionally and deliberately (Hildebrand, 2005). Several anthropogenic noise sources are located in continental shelf and nearshore waters, which are often essential marine habitats (Hildebrand, 2005). Furthermore, these sound sources can have a direct or indirect impact on several marine organisms, leading to changes in the behaviour of individuals, physiology, auditory masking, damage to the auditory system and other physical injuries (Duarte et al., 2021; Kunc et al., 2016; Peng et al., 2015). Some of these effects are acute such as behavioural changes, temporary hearing loss and injuries resulting from exposition to high-intensity brief sounds (Hawkins & Popper, 2016). In contrast, chronic effects arise from prolonged exposure and include physiologic stress and development disabilities. Both effects can impair vital functions, such as physical fitness, predation avoidance, efficiency in foraging and reproductive performance (Hawkins & Popper, 2016). Thus, besides being a major threat to marine organisms, anthropogenic noise may also influence the ecosystem composition and services (Peng et al., 2015).

According to the descriptor 11 of the Marine Strategy Framework Directive (MSFD 2008/56/EC in the EC Decision 2010/477/EU), the sources of anthropogenic noise are divided into: impulsive noise (descriptor 11.1), which is described as a high intensity sound with a short duration and located in space, and continuous low frequency sound (descriptor 11.2), that is characterized by sounds of low intensity but with continuous expression in time and weak spatial directivity (Van der Graaf et al., 2012). Impulsive sounds are produced for example by seismic surveys, marine pile drivers, sonars, and explosions. Continuous low frequency noise is generated by fishing and transport vessels as well as other underwater or surface vehicles (Van der Graaf et al., 2012). Anthropogenic noise sources are becoming more widespread as well as powerful, raising levels of ocean background noise. Anthropogenic noise sources have contributed to increasing ocean ambient noise levels in the last 50 years, leading to higher levels in the medium (1 to 20 kHz) and low (<1000 Hz) frequencie ranges (Hildebrand, 2005).

Since anthropogenic noise leads to changes in the acoustical environment that may have a negative effect on the endurance of species and populations, different intergovernmental institutions address the underwater noise effects on marine species (Rako-Gospić & Picciulin, 2019).

3 UNDERWATER NOISE MONITORING

Due to regulatory requirements to assess the environmental effects of anthropogenic noise and the environmental status of the sea, a growing need exists to monitor and document marine underwater noise levels (Robinson et al., 2014). Despite the effort to report sound levels, it is often difficult to compare different studies because of the use of different acoustic metrics and methods. The applied measurement methods can vary, and the metrics can assume distinct meanings for each specific application (Robinson et al., 2014).

As indicated by Robinson et al. (2014) the sound measurement is limited by the instrumentation performance. Several reports provide advice on requirements for noise monitoring and calibration of equipment to avoid the acquisition of inappropriate monitoring devices, and to ensure that the noise will be monitored in a cost-effective way and with proper data collection (Ainslie et al., 2019; Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012; Vukadin et al., 2018). There are also many scientific papers where background noise has been monitored and reported (Andrew et al., 2011; Cato, 2008, Dudzinski et al., 2011; Mcdonald et al., 2006; Reine et al., 2014; Tougaard et al., 2009; Wenz, 1962; Würsig & Greene, 2002). Some of these articles provide descriptions of the employed measurement system and the methodology for analysis.

3.1 MEASURING EQUIPMENT

A generic underwater noise measurement system consists of a hydrophone, an A/D converter, data transmission or/and data storage device (Vukadin et al., 2018). The hydrophone is an electroacoustic transducer that allows the detection of sounds in the marine environment. The conditioned analog signal from the hydrophone is translated by the A/D converter into digital data form. This data is then saved to the memory to be transferred directly or downloaded to a computer (Vukadin et al., 2018). In addition to the hydrophone, extra sensors can be used such as for temperature, GPS, and depth.

The recording devices can be manually operated or work autonomously (Dudzinski et al., 2011). Autonomous recorders are usually very profitable and have considerably improved the ability to measure ocean noise, representing most of the passive acoustic monitoring systems (Dekeling et al., 2014b; Dudzinski et al., 2011). The performance of both autonomous recorders and manually operated devices must be suitable for their usage purpose (Dekeling et al., 2014b).

Several performance indicators are essential to ensure that the measurement system is fit for purpose: the frequency response and range, the directivity, the system self-noise, the dynamic range and the sensitivity (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018).

3.1.1 FREQUENCY RESPONSE/RANGE

Ideally, the frequency response should extend to a frequency sufficiently high to accurately record the noise spectrum of interest. How high the maximum frequency is will depend on the measurement objective, for example, the maximum frequency transmitted by a particular source (Robinson et al., 2014). For ambient noise monitoring, it is recommended that the system has a flat frequency response (within ±1 dB) in the 5Hz-10kHz band with the option of high pass filtering under 10 Hz (Vukadin et al., 2018).

In order to fulfil the D11.2 criterion the required frequency ranges are the two 3rd octave bands with nominal centre frequencies of 63 Hz and 125 Hz (Van der Graaf et al., 2012). However, the entire system can also record higher frequencies that can be employed for other research purposes. Therefore, the monitoring system should at least include a 10 Hz to 20 kHz frequency range, which also covers the spectrum frequency for criterion D11.1 (10 Hz to 10 kHz) (Van der Graaf et al., 2012). Since most high-grade hydrophones cover a much wider frequency range than needed for the descriptor 11.2, this supplementary range will hardly increase the cost (Robinson et al., 2014; Vukadin et al., 2018).

The noise from propeller of underway ships exhibits a peak in the frequency range 50-150 Hz. Therefore, the two 3rd octave bands are considered for capturing the anthropogenic input from navigation, as well as to minimize the natural sources contribution (Garrett et al., 2016). Furthermore, the 3rd octave bands are frequently utilized in marine mammal masking studies (Jensen et al., 2009; Madsen et al., 2006).

In addition to the two recommended third octave bands, the inclusion of a higher frequency band of 2 kHz for ambient noise monitoring is under discussion, since ship noise contains energy in this frequency band and some marine species, such as fish, e.g. herring, harbour porpoises and seals are able to detect this frequency (BIAS LIFE11 ENV/SE/841, 2016).

Several studies in different locations have already documented low frequency third octave level measurements that ranged from short-term to longer term. For example, noise level measurements were carried out in offshore California over seven years (Andrew et al., 2002), in British Columbia offshore only for 4 months (Merchant et al., 2012a), on the SOFAR channel in the Indian, Pacific and Atlantic Oceans by hydroacoustic long-term monitoring stations (Van der Schaar et al., 2014), and for 2 years in the shallow waters of the Kvarneric´ region in the North-eastern Adriatic Sea (Rako et al., 2013). Besides these measurements, there have also been surveys associated with industrial activity monitoring, such as dredging activities within 20 Hz to 20 kHz in the Harbour of New York (Reine et al., 2014), wind turbine operation in Sweden and Denmark at frequencies below 500 Hz (Tougaard et al., 2009), and Hong Kong port operations for four days (Würsig & Greene, 2002).

3.1.2 DIRETIONALITY

Directivity refers to the hydrophone's property of being most sensitive in a particular direction. The hydrophone must respond equally to noise generated from all directions, that is, an omnidirectional horizontal response (Vukadin et al., 2018). The directionality pattern depends on the frequency and size of the hydrophone. This equipment will show directivity when its size exceeds the acoustic wavelength (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018). In case the wider frequency range is targeted, it is recommended that the hydrophone should be omnidirectional at 20 kHz with ±3 dB tolerance level (Van der Graaf et al., 2012; Vukadin et al., 2018).

3.1.3 SELF-NOISE

The system self-noise is the noise emitted by the hydrophone and the recording system itself when there is no acoustic signal and is a key factor when monitoring low sound levels (Robinson et al., 2014). This noise is normally represented as a spectral density level of noise vs. frequency because of its variation with the acoustic frequency. Self-noise represents the lowest sound level which can be detected in recordings (Vukadin et al., 2018).

It has been recommended by Van der Graaf et al. (2012) that the equivalent self-noise sound pressure level must be no less than 6 dB under the lowest sound level that will be measured in the relevant frequency range so that acceptable signal-to-noise ratio can be obtained when monitoring acoustic signals. Furthermore, by considering that the monitoring is conducted to evaluate anthropogenic noise, it is recommended that the self-noise levels of the hydrophone should be lower than 53 dB re 1 $\mu Pa^2/Hz$ at 63 Hz and below 49 dB re 1 $\mu Pa^2/Hz$ at 125 Hz (Vukadin et al., 2018). In case the hydrophone will be utilized for underwater noise measuring with a wider frequency range, the self-noise must be lower than 30 dB re 1 $\mu Pa^2/Hz$ at 10 kHz (Vukadin et al., 2018).

As documented in previous reports (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018) the values for system self-noise are usually compared with classical empirical curves for continuous noise levels at sea, like the Knudsen (Knudsen, 1948) and Wenz curves (Wenz, 1962).

3.1.4 DYNAMIC RANGE

The system's dynamic range is the amplitude range in which the system reliably measures the acoustic pressure (Dekeling et al., 2014b; Robinson et al., 2014). This extends from the lower measured signal to the greatest signal amplitude that can be monitored without substantial distortion. The dynamic range should preferably be adequate to allow the highest expected sound pressure to be measured accurately without saturation due to the amplifier, the ADC (Analogue to Digital Converter) and the hydrophone (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

Sounds that are way beyond the system's maximum measurement ability (high-amplitude sounds) will clearly lead to distortions in the data that is being measured (Robinson et al., 2014). A signal of too high amplitude may cause saturation of the electronic amplifier, which may take a while for the system to recover from. Nevertheless, the measurement system must be linear over the entire dynamic range.

In the case of certain systems, as the limit of high amplitude is approached, the response might be non-linear because of the limitations in the components' performance, like amplifiers. Consequently, it is recommended not to use a measuring system near the limit of its dynamic range unless it has been verified for linearity (Dekeling et al., 2014b; Robinson et al., 2014).

For the measurement of signals with low amplitude, it is necessary to take precautions to ensure not only that the amplitude of the signal exceeds the system noise level, but to also guarantee that the measured signal is not too low to suffer from quantization noise as a result of the ADC's weak resolution for too low signals (Dekeling et al., 2014b; Robinson et al., 2014). The resolution of the recording should at least be 16 bits, although an optimal system should have 24 bits (Van der Graaf et al., 2012). By using the latest high-resolution A/D converters, this is a minor concern compared with the past. Nonetheless, to achieve properly resolution recorded signals the settings of the system need to be selected (Dekeling et al., 2014b; Robinson et al., 2014).

3.1.5 SENSITIVITY

The hydrophone and measurement system sensitivity must be selected to suit the sound amplitude that is being recorded. The goal in choosing the sensitivity of the system is to prevent a weak signal/noise ratio for low sound levels and to avoid the system's clipping, saturation, and nonlinearity for high levels of sound (Dekeling et al., 2014b; Robinson et al., 2014). The continuous noise recording (MFSD descriptor 11.2) requires hydrophones that are more sensitive than those for impulsive noise monitoring (MFSD descriptor 11.1), due to the higher levels of these sounds (Vukadin et al., 2018). It was recommended by Van der Graaf et al. (2012) that the sensitivity of the system should be between -165 dB re 1 V/µPa to -185 dB re 1 V/µPa. Some previous studies have already followed this recommendation when measuring ambient noise (Garrett et al., 2016; Rako et al., 2013).

For the measurement to be absolute the system's sensitivity should be known, which will require calibration of the system. This calibration is supposed to cover the entire frequency range that is relevant for the application in question. A full calibration is recommended to be carried out prior to and after each sea trial or deployment (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

A system calibration may be performed by either a single component calibration, or a complete calibration of the system. To fully calibrate the system, the hydrophone should be exposed to a sound pressure level that is known and the hydrophone output recordings should be analysed (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012). When calibrating single components, a separate calibration of the hydrophone is made by an acoustic measurement, whereas for the calibration of the other components, known electrical input signals are used. Besides the hydrophone, the components that need to be calibrated are amplifiers, filters, and the Analog to Digital Converter (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

In addition to calibration, it is also important to consider data storage. Despite the existence of many appropriate data formats, no standard format exists for the storage of underwater sound data (Robinson et al., 2014; Vukadin et al., 2018). However, to prevent data quality degradation the format used for storing the data needs to be lossless (e.g., WAV format or equivalent). It is not advisable to use compressed audio data formats, like MP3, for example (Robinson et al., 2014; Vukadin et al., 2018).

3.2 METHODS FOR NOISE MEASUREMENT

The measurement methods may differ according to the objective of the study and the source of noise to be measured, the duration of deployment, the surroundings, the noise frequency and amplitude, and the costing (Robinson et al., 2014).

The sampling methodology depends on the measurement goal. For example, if the aim is only to determine the instantaneous levels of background noise it is reasonable to take a noise snapshot from a deployment at short-term (possibly a couple of hours) (Robinson et al., 2014). When the goal is determining the change in global background noise caused by a specific activity (e.g. a marine renewable energy installation) it is more appropriate to perform a medium-term deployment of maybe a couple of weeks. However, when the purpose is to take measurements to broadly characterize background noise, it is necessary to carry out long-term measurements (Robinson et al., 2014).

For snapshots and medium-term deployments, continuous recordings can be carried out. In the continuous recordings the system measures underwater noise over the whole period of deployment (Robinson et al., 2014; Vukadin et al., 2018). However, to allow long-term deployments that are limited by battery and storage capacity, it may be necessary to adopt a duty cycle where the recorder is on only a portion of the time. Duty cycle recording is an on-off procedure, which means that data is recorded during some time (on) following the off period when the system is inactive (Robinson et al., 2014; Vukadin et al., 2018). This improves both memory utilization and battery life. The standby and active periods are established so that all key underwater noise characteristics are detected during the entire period of deployment. The suitable duty cycle is dependent on the measurement goal and the equipment limitations (Robinson et al., 2014; Vukadin et al., 2018).

The spatial sampling should also be considered as measurements may need to be taken at one or more locations to obtain a good understanding of the soundscape (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018). For example, if an estimation of the global ambient noise in an area is required, the hydrophone should ideally not be positioned near a local source of loud noise that will overwhelm the sound field. When deciding on the site for long-term deployments, the depth of water at the location of measurement must be taken into account. The hydrophone position in the water column will be different depending on the deployment methodology employed (Robinson et al., 2014; Vukadin et al., 2018). When sound propagates in shallow water, there is a lower cut-off frequency below which there is no sound propagation. The chosen location should not be so shallow that sound from low frequency sources far away cannot reach the hydrophone if the low frequency sound is of concern. The site should preferably have several other features (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018) such as:

- Slightly variable bottom bathymetry;
- Clear visibility with no significant bathymetric characteristics in between (e.g. sandbanks);
- Not directly beneath a particular traffic route;
- Far from areas of fishing where trawl disruption/damage is probable.

The key goals of the chosen measurement setup include sampling the noise level at the proper spot(s) in the water column over the duration needed for the implementation; and minimizing non-acoustic signals generated by the platform and the hydrophone (Dekeling et al., 2014b; Robinson et al., 2014).

There are several typical deployment setups, of which many are described in the following research papers (Cato, 2008, Dudzinski et al., 2011; Enguix et al., 2019; Haxel et al., 2019; Lammers et al., 2008; Merchant et al. 2012b; Pine et al., 2016; Soares et al., 2020a; Southall et al., 2020). These setups can be divided into stationary deployments (bottom-mounted systems), that are meant to be deployed at a site over a long period, and mobile deployments (surface-based systems, drifting systems, and mobile platforms) that are portable and deployed for brief intervals or that record while on the move (Dekeling et al., 2014b; Merchant et al., 2015; Robinson et al., 2014; Vukadin et al., 2018).

3.2.1 STATIONARY DEPLOYMENTS (BOTTOM MOUNTED SYSTEMS)

The stationary systems are more suitable for long-term surveys. These systems can be utilized to monitor underwater noise through continuous recordings, or by time sampling using a specified duty cycle for months or weeks intervals. This allows that the data is sampled, for example, under several meteorological conditions (Robinson et al., 2014).

In the bottom mounted deployments, a general underwater noise measurement system is attached to the seabed by anchors or ballasts (Figure 1). The shape and weight of the anchor should be adjusted to the type of bottom, for example, for hard bottoms the system would require heavier anchors as the rubbing between the anchor and the bottom is low (Vukadin et al., 2018). To guarantee the functionality of the system while submerged in water, all parts (excluding the hydrophone) are placed in a waterproof container (Vukadin et al., 2018). This container is connected to the flotation. The hydrophone is normally placed near the housing and is connected to it by a short cord (Figure 1). A battery that provides the system's power is also placed within the container. Underwater noise data is recorded by the system during the period of its installation, and after its recovery, the data is downloaded for storage and processing (Vukadin et al., 2018).

The system recovery involves using an acoustic release system (Figure 1A) or a floating buoy fixed on the seafloor by an anchor (Figure 1B) (Robinson et al., 2014; Vukadin et al., 2018). The acoustic releaser, which is an oceanographic device, can be used to deploy and recover equipment from the seabed, where recovery is remotely activated via an acoustic command signal (Vukadin et al., 2018). A unique acoustic command exists (or can be defined) for each releaser, and after getting this command, it opens a hook and frees itself and the measurement system from the anchor. As a result of the attached flotation, the releaser and the measurement system raise to the surface of the sea. Alternatively, the bottom system can be connected to a surface buoy and retrieved by the rope tied to the buoy (Figure 1B) (Vukadin et al., 2018).

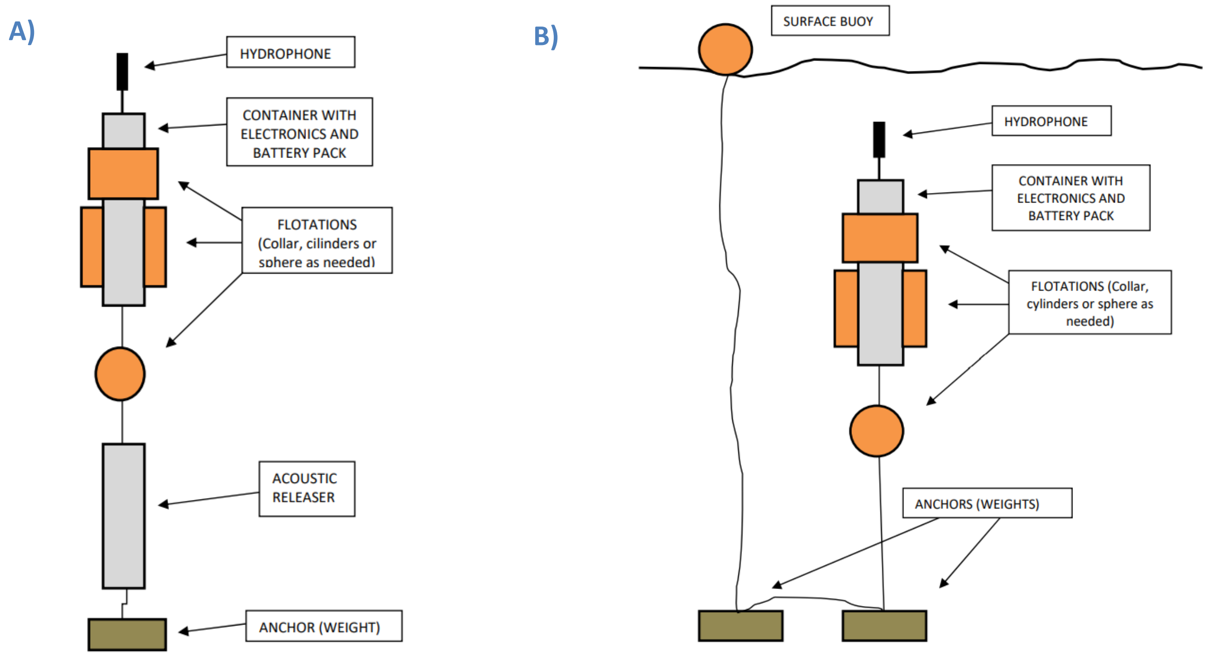

Figure 1. Configuration of bottom mounted systems for measuring underwater noise. A)- System with acoustic releaser; B)- Deployment using surface buoy (scheme obtained after Vukadin et al., 2018).

For an optimal deployment, the data would be transmitted directly to the land base via a modem link, satellite, or cable. The advantage of such deployment is the almost real-time availability of data and the possibility to verify the functionality of the system. Nevertheless, these setups are costly and therefore a much economical option for many surveys are autonomous recorders (Table 1) which can be moored to the sea bottom and where the data is only accessible from time to time after recovery (Merchant et al., 2015; Robinson et al., 2014).

The stationary deployments have been used in several previous studies to measure underwater noise at different locations (Table 1) and present both advantages as well as disadvantages (Table 2).

Table 1: Examples of underwater noise measurement using stationary deployments in different regions.

Region	Frequency range	Recording Duration	Autonomous Recorders	Reference
Hawaiian Islands	20 Hz to 20 kHz	Every 15 min for 30 s	Ecological Acoustic Recorder (EAR)	Lammers et al., 2008
England	5 Hz to 8 kHz	Continuous recordings in 30-min blocks	Autonomous Multichannel Acoustic Recorder (AMAR)	Merchant et al. 2012b
Portugal, Ria Formosa	-	Every 10 min for 90 s	DigitalHyd SR-1	Soares et al., 2020a
St. Lawrence Island, Alaska	20 Hz to 10 kHz	Duty-cycled recordings for 5 or 10 min	DSG and DSG-ST	Southall et al., 2020

Table 2: Advantages and drawbacks of the bottom mounted systems (Robinson et al., 2014; Vukadin et al., 2018).

Advantages	Disadvantages
- Deployments are relatively inexpensive and simple - The noise induced by the system is minimal - Deployment periods can be long and are independent of weather conditions - Data can be recorded at remote locations	- The system functionality cannot be verified during the deployment - Possibility of losing or damaging the equipment - Data is only available after deployment - Not suited for locations with strong currents

3.2.2 MOBILE DEPLOYMENTS

3.2.2.1 SURFACE BASED SURVEYS

Surface based systems are recommended for short-term noise measurements in shallow water. In these systems a surface platform is used, which is usually a vessel that may be drifting or anchored (Robinson et al., 2014; Vukadin et al., 2018). All parts of the system, apart from the hydrophone, are placed on board the vessel (Figure 2). The hydrophone hangs from the boat at the required depth and is connected to the onboard equipment via a cable (Vukadin et al., 2018). To reduce platform self-noise from the cable strum and boat movement, the cable connected to the equipment on board can be used to connect the hydrophone to a surface buoy (Figure 2) (Vukadin et al., 2018).

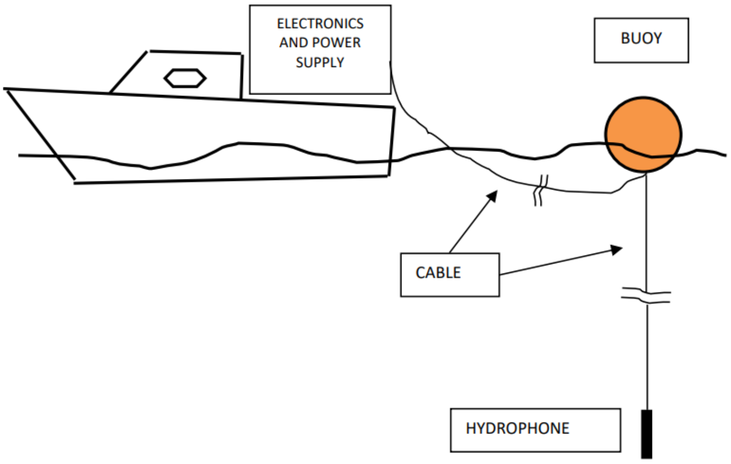

Figure 2. Configuration of a vessel-based system for measuring underwater noise using a surface buoy for mitigating platform noise (scheme obtained after Vukadin et al., 2018).

This system is very easy and simple to deploy and recover since only the auxiliary buoy and the hydrophone are deployed and retrieved from the boat. Furthermore, surface-based systems are the most common starting point for underwater noise measures since it is easy to find small boats and the measurement equipment can be readily accessible (Vukadin et al., 2018). There are also other benefits and some drawbacks when using this system (Table 3).

Table 3: Advantages and disadvantages of the vessel-based systems (Robinson et al., 2014; Vukadin et al., 2018).

Advantages	Disadvantages
- A large area can be covered in a cost-effective way	- Dependent of weather conditions
- Small boats and equipment for general use can be employed	- Deployments are more likely to be short term
- Deployments can be mobile and quick and recordings are carried out in real time	- Higher costs for longer deployment periods
- No danger of data loss or equipment damage	- Noise induced by the vessel and cable movement*

* The noise from the boat movement can be minimized if the hydrophone is deployed at a greater depth

3.2.2.2 DRIFTING SYSTEMS

Drifting systems are typically used for underwater noise measurement in tidal flows or strong currents that would produce high flow noise levels if the system's hydrophone were stationary (Vukadin et al., 2018). These systems can be ship-based, although recently autonomous drifting recorders, such as gliders, are being utilized. These recorders have the benefit of minimizing the effects of flow noise in areas of high tidal flow (Robinson et al., 2014).

In this setup the general underwater noise measurement system is suspended by a buoy on the surface driven by waves, wind, tide or current (Figure 3). All the components of this system, excluding the hydrophone, are placed either within the buoy or in a waterproof container that is hanging from the buoy (Vukadin et al., 2018). The hydrophone is suspended at the required depth and is linked to the surface buoy by a cable (Figure 3). For the hydrophone to remain stationary in relation to the horizontal movement of the water a drogue (for example, “underwater parachute” or anchor) is utilized (Figure 3). The drogue also dissociates the movement of the buoy from the hydrophone (Robinson et al., 2014; Vukadin et al., 2018).

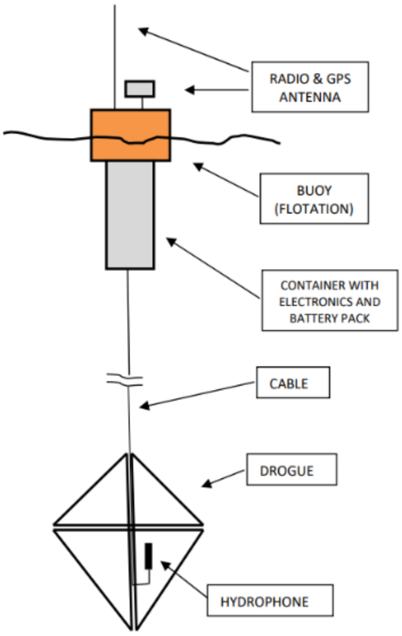

Figure 3. Typical setup of a drifting system for underwater noise measurement (scheme obtained after Vukadin et al., 2018).

In the drifting system a GPS receiver can be used to provide a positional data log (Figure 3). The acoustic data can be saved in memory and downloaded at the end of the installation period to the external desktop. However, the data can also be transmitted in real time by satellite data link or radio (Figure 3) (Robinson et al., 2014; Vukadin et al., 2018).

The implementation and recovery of drifting systems is relatively easy and cheap since they do not require anchors, they are much more lightweight than, for example, bottom mounted systems and their deployment can be made from smaller boats. To recover the system the buoy is raised from the surface along with the remainder of the system (Vukadin et al., 2018). Furthermore, this system presents other advantages and a few disadvantages (Table 4).

Table 4: Advantages and disadvantages of the drifting systems (Robinson et al., 2014; Vukadin et al., 2018).

Advantages	Disadvantages
- Capacity to measure underwater noise in strong currents - Data can be measured almost in real time - Measurements are carried out at more than one location - Data can be transmitted via radio or satellite	- Not suitable for long-term deployments - The system can be affected by noise from floats and moorings - Possibility of equipment damage or loss - Results are more difficult to process and analyze due to its mobility

Besides the described mobile systems (surface-based and drifting systems), in some studies autonomous underwater vehicles (AUVs), gliders or wavegliders are used (Table 5). These underwater vehicles are freely drifting platforms that can be equipped with a hydrophone and an acoustic data logging system and be deployed over several hundred days (Merchant et al., 2015). The wavegliders are propelled by solar and wave energy and can operate either individually or in fleets and provide data in real time for up to a year, without fuel (Hine et al., 2009).

All mobile deployments have been used in previous studies to monitor underwater noise at several regions (Table 5).

Table 5: Underwater noise measurement using mobile deployments in several regions.

Region	Types of noise sources	Frequency sample	Recording Duration	Type of mobile deployment	Reference
New Zealand	Ambient noise	10 Hz to 60 kHz	15 min	Drifting system	Pine et al., 2016
Spain	Impulsive and Ambient noise	10 Hz to 98 kHz	Series of 3 min	Vessel-based system	Enguix et al., 2019
U.S. Pacific Northwest coast	Ambient noise	-	Continuous recordings archived every 10 minutes	Glider	Haxel et al., 2019

3.2.3 NOISE SOURCES RELATED TO DEPLOYMENT

The measured data can be contaminated not only by the measurement system's self-noise but also by signals coming from the deployment system or the platform. Therefore, care should be taken in system deployment design to prevent these sources from contaminating the data. The most common sources that contribute to platform self-noise and that should be minimized are the flow noise, the hydrophone cable strum, the hydrostatic pressure fluctuations, the boat noise, the mechanical and electrical noise (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

Some methods to reduce flow noise have been recommended by Van der Graaf et al. (2012) such as placing the hydrophone near the seafloor where there is less flow and using surface buoys.

Regarding the noise emitted by the cable strum, that occurs when the cables are pulled by the currents thus producing low frequency noise, it can be minimized by using bottom mounted systems (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

Systems that are placed from the surface can be affected by the action of waves, which can cause pressure fluctuations of low frequency but yet of high amplitude. To minimize this noise, it was recommended that the hydrophone should be mounted from the seafloor instead of the sea surface, by either using a sub-surface buoy arrangement (Figure 4) or a bottom-mounted frame (Figure 1A) (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

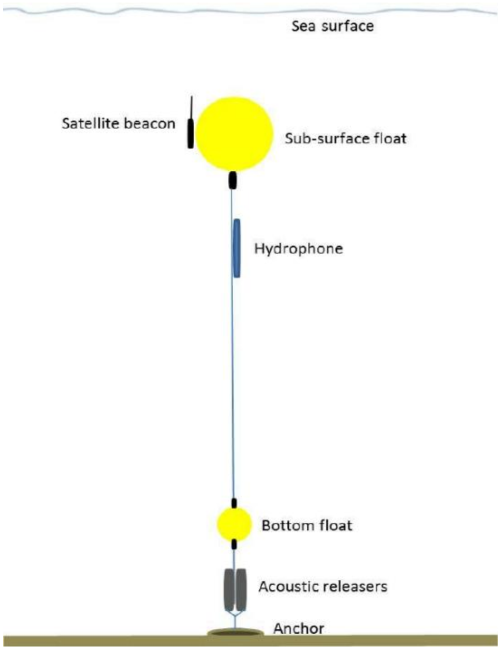

Figure 4. Configuration of a bottom-mounted system with a sub-surface buoy arrangement (scheme obtained after Shabangu, 2014).

In case of deployments from the surface, the hydrophone must be decoupled from the surface movement using, for example, motion dampers (e.g. a buoy) or/and elastic rope to reduce the issue (Figure 2) (Robinson et al., 2014).

When deployments are carried out from a boat, the engines and the generator should be turned off and the least possible noise should be made in the boat itself by the crew and machinery (Robinson et al., 2014). Vessel-based deployments are subject to another noise source, which is the noise from wave action on the hull of the boat. This noise will be worse depending on the hull type and may be minimized by orientation of the boat to the waves, and by deploying the hydrophones on long cables by use of buoys or floats to extend the boat's distance from the hydrophones; yet this is hard to eliminate entirely in practice (Robinson et al., 2014).

The mechanical noise includes the impact of sediment or/and debris on the hydrophone, the noise of biological abrasion and the cables and hydrophone rubbing against one another (Dekeling et al., 2014b; Van der Graaf et al., 2012). Van der Graaf et al. (2012) recommended to avoid having metal in contact with metal, the use of chains on the supports and deploying the hydrophone too near the seafloor, to minimize this noise.

In relation to electrical noise, the system of acquisition and the hydrophones must have an adequate electrical shielding to reduce the noise (Robinson et al., 2014).

3.2.4 AUXILIARY MEASUREMENTS

Any auxiliary data that might be of importance should be recorded, as it may correlate with the noise levels monitored. Although this is generally important, it is especially helpful in the measurement of ambient noise (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012). Recording auxiliary data allows an investigation of the recorded data dependencies on other ambient conditions, like climate. Some of the auxiliary data can be collected from other sources, however if they are measured on-site, this might demand the use of auxiliary equipment (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012).

It has already been recommended (Dekeling et al., 2014b; Robinson et al., 2014; Van der Graaf et al., 2012) to register several relevant auxiliary data such as:

- State of the Sea;
- Rainfall rate and other precipitations;
- Wind speed and related measurement height;
- Depth of water and tidal fluctuations in water depth;
- Depth of the hydrophone in the water column;
- Temperature of water and air;
- GPS locations of the underwater noise measurement systems;
- Type of seafloor;
- Conductivity, temperature and hydrostatic pressure profile according to the water column depth using a CTD probe;
- Seawater pH using a pH meter;
- A monitor for vessels presence at the site where measuring’s are being done e.g., the Automatic Identification System (AIS);
- The presence of any animals in the area and any activity generating noise from a distance.

3.3 PROPAGATION MODEL CHOICE AND MEASUREMENT UNCERTAINTIES

Several factors influence the sound propagation in the sea and add to the propagation loss, that is, the signal reduction while the sound is propagating from the source to the receptor (Jensen et al., 2000). In general, these factors include: the sound's geometric propagation away from the source; the sound absorption by the seafloor and the seawater; the sound refraction because of the sound velocity gradient and the depth of source and receiver (Jensen et al., 2000). Therefore, it is important to assure that the propagation model used accounts for the relevant physical propagation events (Robinson et al., 2014), including some potentially influential factors like: the range-dependent bathymetry, including the dependence on variable water depth; the speed of sound, particularly for deeper waters; the dependence on frequency, including water absorption; the characteristics of the seafloor; and the interaction with the surface of the ocean (Robinson et al., 2014).

Ideally, a model that has been checked against previous experimental data, or compared with other propagation models, or verified for consistency with measured data from actual experimental work, should be used (Robinson et al., 2014). The best validation of a propagation model is by comparing it to experimental data from transmission loss measurements. If these measures are on hand for certain places, a straight comparison of the model predictions with the recorded data would show the probable accuracy and give reliability to the model predictions for which no measured data are available (Robinson et al., 2014).

Regarding uncertainty, it is an estimate of the value range within which the true value is deemed to lie within a specified confidence level. A measurement's value is highly constrained without some estimation of uncertainty. There are potentially several uncertainty sources when measuring underwater noise (Robinson et al., 2014; Vukadin et al., 2018):

- Calibration of the equipment;
- Source and receiver position;
- Deployment or/and platform induced sound;
- Validation of any hypotheses made;
- Environmental factors (for using in a propagation model).

It can become very difficult to assign values of uncertainty to results that are often presented in the form of "error bars". Nevertheless, it is worth to consider the uncertainty sources and try to perform some assessments so that the limits can be placed on the results (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018).

The uncertainties can be classified in two categories depending on the method employed to estimate their numerical values: Type A, which is a method for evaluating uncertainty by statistical analysis of series of observations; and Type B, which is a method of assessing uncertainty by other means than statistical analysis of series of observations (Robinson et al., 2014; Vukadin et al., 2018).

Several steps for evaluating uncertainty have already been recommended (GUM, 2008; Robinson et al., 2014), such as:

- Remove unwanted signals;
- Evaluate the uncertainty in the calibration of the equipment;
- Verify the results consistency;
- Confirm any assumptions made;
- Perform a sensitivity analysis;
- List the contributions of uncertainty and attribute values.

4 DATA ANALYSIS

When performing underwater noise data analysis, the underlying objective can be a determinant factor in choosing the method of analysis. The analysis may have a variety of purposes like, for example, to provide a descriptor of the global level of noise, compare the levels of noise with other sites and to describe the soundscape and the noise nature (Robinson et al., 2014).

4.1 REPRESENTATION OF FREQUENCY

Noise data is normally plotted in the frequency domain. A time-frequency representation like a waterfall plot, which represents the noise levels variation in time/space (Abrahamsen, 2012), or a spectrogram is recommended to illustrating the time variation in frequency content for a temporal varying signal. Time and frequency are represented on the horizontal and vertical axes in a spectrogram, and spectral levels are plotted using colour mapping. There should be a choice about the filter bandwidth to be employed: narrowband spectrogram provides higher frequency resolution and broadband spectrogram provide higher temporal resolution. The ideal choice will depend on the sound type and the needed information from the spectrogram (Dekeling et al., 2014b; Robinson et al., 2014).

4.2 METRICS

There are several distinct metrics that might be used as sound pressure measurements and some of the metrics have been recommended to express ambient noise and impulsive noise (Dekeling et al., 2014b; ISO1996-1, 2003; Morfey, 2001; Robinson et al., 2014; Van der Graaf et al., 2012; Vukadin et al., 2018) (Table 6).

Table 6: Recommended metrics for measuring continuous and impulsive noise levels.

	Continuous noise	Impulsive noise
Metrics	Sound Pressure Level (SPL)	Pulse Sound Exposure Level (SEL)
	Sound Exposure Level (SEL)	Cumulative Sound Exposure Level (SEL) (For a series of pulses)
	-	Peak sound pressure level
	-	Peak-to-peak sound pressure level

The Sound Exposure Level metric can be used for continuous noise sources if the SEL over a frequency band is integrated across a fixed time period instead of across individual pulses or events (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018). A 1 second period is usually used (Southall et al., 2008).

Regarding impulsive noise it might also be helpful to estimate the peak compression sound pressure level, the peak rarefaction sound pressure level, the pulse repetition frequency, and the pulse duration (Dekeling et al., 2014b; Robinson et al., 2014; Vukadin et al., 2018). The Sound Exposure Level, for an acoustic pulse, is calculated over the pulse duration, which is typically defined as the time occupied by the pulse's central portion, where 90% of the energy of the pulse lies. The SEL for each pulsed noise event may also be aggregated by summing to calculate the total Sound Exposure Level to assess the environmental impact along an entire pulse sequence, or over a prolonged time period (Madsen, 2005; Southall et al., 2008).

When analysing continuous noise, averaging of the measured data is necessary because instantaneous sound pressure values are fluctuating continuously, and any snapshot at a particular moment in time may not represent the statistical variation of the values (Dekeling et al., 2014b; Robinson et al., 2014). In order to average the data, the recorded data is divided into snapshots. For each temporal sequence of snapshots, the Sound Pressure Level is then computed at each analysis frequency. The snapshot time selection will vary depending on the type of data available, for example, if the duty cycle consists of 5-minute sequence recordings then the time of the snapshot cannot be more than 5 minutes although it might be shorter (Dekeling et al., 2014b; Robinson et al., 2014).

There are several averaging methods that have been employed for underwater noise data, and a number of articles and reports in response to MSFD compare the usefulness of distinct methods and make various recommendations (Dekeling et al., 2014a, 2014b, 2014c; Merchant et al., 2012a; Robinson et al., 2014; Van Der Schaar et al., 2014). The common average metrics that have been employed are the arithmetic mean, the median, the geometric mean and mode (Table 7) (Dekeling et al., 2014b; Merchant et al., 2012a; Robinson et al., 2014; Van Der Schaar et al., 2014). The arithmetic mean, and the median were recommended to be used to express the continuous noise values (Dekeling et al., 2014b; Robinson et al., 2014).

Table 7: Description of the common average metrics and their advantages and disadvantages.

Average Metrics	Definition	Advantages	Disadvantages
Arithmetic mean	Average square sound pressure	Invariant with snapshot time choice Can be compared with other studies	Influenced by very high amplitude sounds
Median	The 50th percentile	Less affected by high amplitude sounds	Dependent on the snapshot time chosen
Geometric mean	Arithmetic mean calculation over the level's values in decibels	Easy to estimate if the data is already present as decibels	Dependent on the snapshot time chosen
Mode	The maximum of the probability distribution	Can be statistically relevant	Not recommended by Robinson et al. (2014)

5 MONITORING OF UNDERWATER NOISE IN EUROPE

Since the MSFD has the goal of achieving good environmental status, each Member State must assess the marine waters' environmental status, develop a program of monitoring, determine good environmental status, and implement a programme of actions (Van der Graaf et al., 2012).

Some projects, through their research and results, are supporting European nations in fulfilling the Marine Strategy Framework Directive requirements. One of these projects is the Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS) where 11 institutes from the countries bordering the North Sea are involved: the Netherlands, the United Kingdom, Germany, Denmark, Sweden, Belgium and Norway. The purpose of this project is to develop a framework for a fully functional joint monitoring program for ambient noise in the North Sea. Its findings will provide the needed tools for planners, managers and other stakeholders to incorporate ambient noise impacts into their evaluation of the North Sea's environmental status, and to assess policies to enhance the environment.

In the JOMOPANS project, ocean measurements are matched with noise maps from numerical modeling to evaluate quantitative sound levels in the ocean. In this project 14 measurement stations were deployed around the North Sea (Kinneging, 2019). The sites were selected to obtain measures of the different noise conditions expected to be encountered in the North Sea basin. Some of the measurement stations are based close to shipping lanes, whereas others are situated in areas that are relatively quiet. Most of the stations are covering the North Sea at a depth of 10 to 60 meters, however there is one station that is in the Norwegian Trench at 300 meters. To obtain sound levels that are statistically significant for every season, it was stipulated that measurements would be carried out for at least one year (Kinneging, 2019).

Another project is the Joint Framework for Ocean Noise in the Atlantic Seas (JONAS) where nine research partners from European countries bordering the Atlantic such as Ireland, U.K., France, Portugal, and Spain are participating. This project aims to address the threats of noise pressures like navigation, construction, and offshore surveys on marine biodiversity, with a focus on sensitive species, by enhancing the monitoring of ocean noise and the prediction of risks. The JONAS project also intends to fulfill the policy makers' needs for a cost-effective and consistent approach to the requirements of MSFD.

In this project a hydrophone was mounted on a waveglider to make a crossing of 1750km from the Azores to Gran Canaria to record the sounds of marine mammals for approximately 2 months. Furthermore, in the JONAS project, vessel noise measurements were carried out in the southern area of the Faial and Pico islands during the entire month of June 2018 (Soares et al., 2020b). Three receivers were installed in different locations at depths of 200 and 484 meters. For recording the acoustic data, systems attached to the bottom by anchors with acoustic releasers and autonomous recorders, Ecological Acoustic Recorder (EAR), were used (Soares et al., 2020b).

In summary, although there are already some projects with different countries monitoring underwater noise, it is important to initiate more international collaboration projects with similar methodologies to allow the comparison of results and to fulfill the MSFD requirements (OSPAR Commission, 2012; Thomsen et al., 2021).

6 CONCLUSIONS

When monitoring underwater noise levels, it is important to follow the recommendations provided by the MSFD reports and previous studies to purchase appropriate monitoring devices and to ensure that noise will be measured in a cost-effective way with proper data collection. Furthermore, it must be determined whether measurements will be made for impulsive or continuous noise, since the choice of some measurement systems (e.g. frequency response/range and sensitivity) and metrics will depend on the noise sources being measured.

However, even following the recommendations provided in this review, underwater noise monitoring can be a challenging task from different points of view. Although different methods and equipment are available, it is clear that for the long-term monitoring required for the purpose of MSFD descriptor 11.2, that bottom-mounted systems will be the most suitable. Nevertheless, long-term monitoring also brings some challenges due to the growing demand for autonomous recorders. These recording devices can be implemented in different ways, such as by integrated the hydrophones in self-powered systems (e.g. solar energy) with data transmission to land (e.g. maritime buoys or opportunistic platforms) or using the autonomous recorders attached to cables. Depending on the duration of the monitoring period, manually operated devices that include a set of equipment with a hydrophone and an independent recording system can also be used.

Underwater noise levels are highly dependent on propagation conditions. Therefore, selecting the site for the systems deployment is an important step in the process. This should consider not only the objective of the study and the equipment accessibility for maintenance but also the spatial and temporal distribution of noise sources. To that end, in what relates to the implementation of MSFD, guidance is already provided. Additionally, the use of models can be useful for a preliminary site-selection.

Due to the increasing need for underwater noise monitoring, there are already some projects with different European countries engaged in this monitoring to meet the requirements of the MSFD. However, it is important to keep promoting the discussion and awareness about noise pollution in the ocean and its impacts on marine life so that more countries can have a role in the underwater noise monitoring.

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8 ANNEX I. LIST OF ABBREVIATIONS

ADC	Analogue to Digital Converter
AIS	Automatic Identification System
AMAR	Autonomous Multichannel Acoustic Recorder
AUVs	Autonomous Underwater Vehicles
CTD	Conductivity, Temperature and Depth
EAR	Ecological Acoustic Recorder
GPS	Global Positioning System
JOMOPANS	Joint Monitoring Programme for Ambient Noise North Sea
JONAS	Joint Framework for Ocean Noise in the Atlantic Seas
MSFD	Marine Strategy Framework Directive
SOFAR channel	Sound Fixing and Ranging channel
SEL	Pulse Sound Exposure Level
SPL	Sound Pressure Level
USV	Unmanned Surface Vehicle


underwater noise
JUMP
Cofinanciado por:
REPÚBLICA PORTUGUESA
MAR
fundoazul
underwater noise
JUMP
Partners:
WavEC
ISPA
MARE
Ciências ULisboa
LNEC LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL
Porto de AVEIRO
museudabaleia
inGeea
FÓRUM OCEANO
oceans ON!
Quercus