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

Deliverable

D3.5 Best practice guidelines on continuous underwater noise measurement (criterion D11C2)

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3	Universitat Politècnica de València	UPV	Spain
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7	Permanent Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area	ACCOBAMS	Monaco
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Abstract

This document is the Deliverable “D3.5 Best practice guidelines on continuous underwater noise monitoring (criterion D11C2)” of the QUIETMED project funded by the 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 Marine Strategy Framework Directive (2008/56/EC). 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 D11C2) iii) development of a joint monitoring programme of impulsive noise (Indicator D11C1) based on a common register, including gathering and processing of available data on underwater noise.

This document presents the best practice, guidelines and recommendations on continuous underwater noise measurement which is part of standardised method for monitoring and assessment for criterion D11C2 of Decision 2017/848/EU. This deliverable is aimed in bringing basic knowledge and experience in the continuous underwater noise measurement thus insuring common approach of all partners to this issue. Furthermore it gives state of the art and best practice in this area of expertise. Also, guidelines and recommendations for the implementation of the best practice to the pilot deployments foreseen by the QUIETMED project are given.

The document is organized in four chapters and two annexes. After the introduction, state of the art of the continuous underwater noise measuring methodologies is given. The generic underwater noise measuring system is described as well as methodology specific measuring systems, namely bottom mounted systems, drifting systems, surface based systems and land based systems. After that, recommendations of best practices on continuous underwater noise measurement in the Mediterranean Sea are given including recommendations for hydrophones and measurement instrumentation (front end electronics amplification and filtering, A/D converter, data storage) and data storage and handling. Overall recommendations for the measuring system specifications are given and the importance of assesing measurement uncertainity is disscussed. In annexes basic acoustic quantities and metrics are defined to be used troughtout the whole project and shallow water specific environmental dependence is disscused. The guideline for the assesment of lower cut-off frequency in shallow water is given.

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List of Abbreviations

CTN	Centro Tecnológico Naval y del Mar
IEO	Instituto Español de Oceanografía
UPV	Universitat Politècnica de València
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UoM	The Conservation Biology Research Group, the University of Malta
IOF	Institute of Oceanography and Fisheries
FORTH	Foundation for Research and Technology - Hellas
MSFD	Marine Strategy Framework Directive

1 Introduction.

The QUITMED 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 Marine Strategy Framework Directive (2008/56/EC).

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- ✓ 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 review of 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 threshold at MED 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 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 Ecosystem Approach Process (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 Monitoring Guidelines of TG Noise).
- ✓ Establish guidelines on how to perform sensor calibration and mooring to avoid or reduce any possible mistakes for monitoring ambient noise (D 11.2.1). 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 (D 11.2.1).
- ✓ Implement a Joint register of impulsive noise (D11.1.1) 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 1-1.

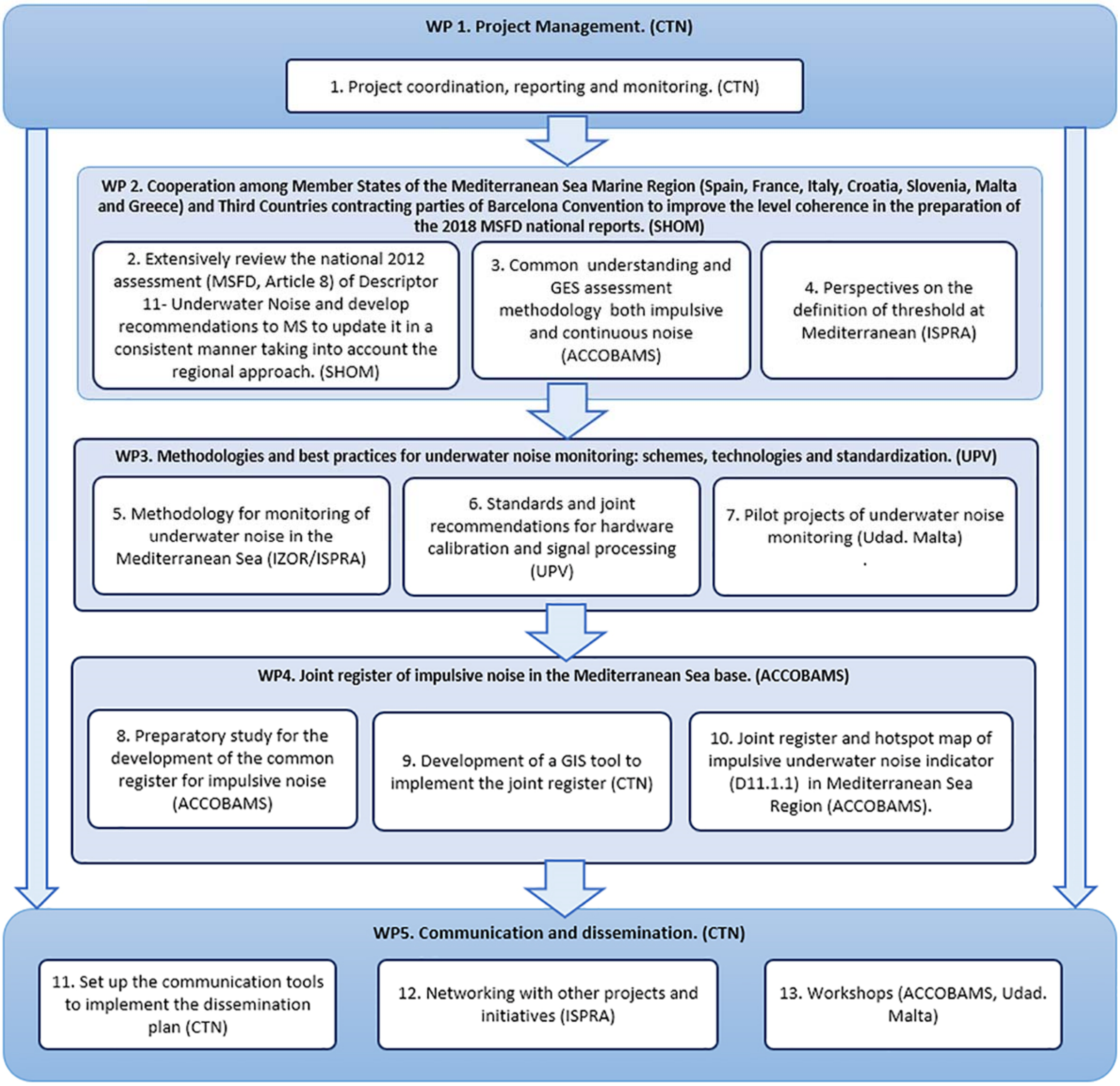


Figure 1-1 Work Plan Structure

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.

This document is deliverable of the Action 5 (*Methodology for monitoring underwater noise in Mediterranean Sea*) of work package 3. It presents the best practice, guidelines and recommendations on continuous underwater noise measurement which is indicator D11C2 of Decision 2017/848/EU. This deliverable is aimed in bringing basic knowledge and experience in the continuous underwater noise measurement thus insuring common approach of all partners to this issue. Furthermore it gives state of the art and best practice in this area of expertise. Also, guidelines and recommendations for the implementation of the best practice to the pilot deployments foreseen by the QUIETMED project are given.

The document is organized in four chapters and two annexes. After the introduction, state of the art of the continuous underwater noise measuring methodologies is given. The generic underwater noise measuring system is described as well as methodology specific measuring systems, namely bottom mounted systems, drifting systems, surface based systems and land based systems. After that, recommendations of best practices on continuous underwater noise measurement in the Mediterranean Sea are given including recommendations for hydrophones and measurement instrumentation (front end electronics amplification and filtering, A/D converter, data storage) and data storage and handling. Overall recommendations for the measuring system specifications are given and the importance of assesing measurement uncertainity is disscussed. In annexes basic acoustic quantities and metrics are defined to be used troughtout the whole project and shallow water specific environmental dependence is disscused. The guideline for the assesment of lower cut-off frequency in shallow water is given.

2 International standards of interest

- ✓ ISO 18405:2017 Underwater acoustics - Terminology
- ✓ IEC 60565 - 2006 (EN 60565: 2007), Underwater acoustics-Hydrophones - Calibration in the frequency range 0,01 Hz to 1 MHz, International Electrotechnical Commission, Geneva, Switzerland, 2006.
- ✓ ANSI/ASA S1.20-2012, Procedures for Calibration of Underwater Electroacoustic Transducers, American National Standard Institute, USA, 2012.
- ✓ ISO 1996-1:2003(E), Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures. International Organization for Standardization, Geneva, 2003.
- ✓ ANSI/ASA S12.64-2009/Part 1, 2009. Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements, American National Standard Institute, USA, 2009
- ✓ JCGM 100:2008, GUM 1995 with minor corrections, Evaluation of measurement data - Guide to the expression of uncertainty in measurement, Working Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG 1).

3 State of the art of the continuous underwater noise measuring methodologies

3.1 Generic underwater noise measuring system

A generic single channel continuous underwater noise measuring system, shown in Figure 3-1, consists of a hydrophone, signal conditioning electronics, A/D convertor, data storage and/or data transmission device.

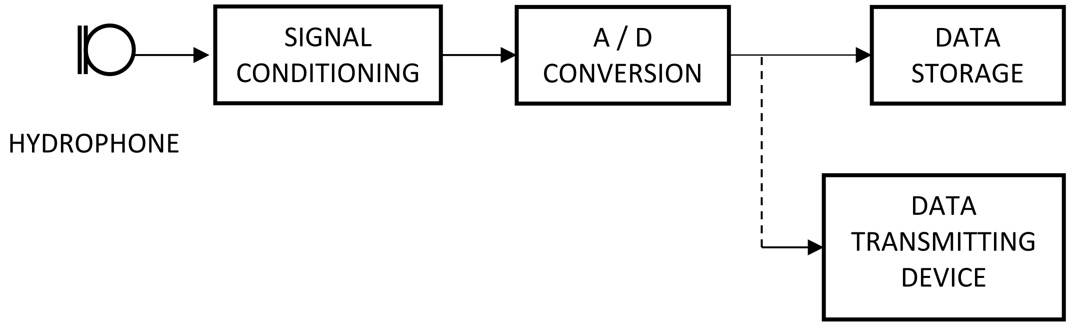


Figure 3-1 A generic single channel continuous underwater noise measuring system

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 variations in electrical voltage on its output. The output of the hydrophone is impedance matched, amplified and frequency shaped (filtered) by the signal conditioning electronics. At the high end of the spectrum the filtering is needed to avoid aliasing (low pass filtering). At the low end of the spectrum filtering is needed to avoid low frequency pressure variations not related to underwater noise but mainly to deployment related issues (high pass filtering). A/D converter converts analogue conditioned signal from hydrophone to digital form of data. Low pass filtering is sometimes done in the A/D convertor according to its sampling settings. 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. Allthough continuous and intermittent recordings differ in recording periods, in both cases recordings (while recording is active) consist of number of shorter parts (time bins) in which the sound pressure level is averaged.

Beside the hydrophone (acoustic sensor), the generic continuous underwater noise measuring system may employ additional sensors such as GPS, temperature, depth etc.

In the broader sense a generic underwater noise measuring system would include equipment for the deployment and recovery of the measuring part of the system. This equipment depends on the specific methodology used (e.g. drifting, bottom) and may include acoustic releasers, anchors, cable and cable drivers, drogues etc.

Depending on the requirements of measurement, multiple channels may be required.

3.2 Methodology specific measuring system

3.2.1 Bottom mounted systems

In case of the bottom mounted systems a generic continuous underwater noise measuring system is deployed on the sea bottom. All system parts except the hydrophone are placed into the waterproof pressure resistant housing (container) to ensure their functionality under the water. The hydrophone is usually packed separately but close to the container to which it is connected with a short cable. The power is supplied from battery pack also placed inside the container. The system stores (records) the underwater noise data for the period of its deployment. After it is recovered from the bottom, data are downloaded to the external computer for final storage and processing. The most common memory media are memory cards or hard disc and the downloading can be done by connecting to the system container with some kind of interface cable. As some systems are designed to record large amounts of data (hundreds of Gbytes) some system require removing memory device(s) from the container and direct download to external computer to enable data downloading within acceptable time. The design of the system will be the tradeoff between anticipated amount of data (which is the function of the deployment period required, resolution and sampling) and the memory size and battery power available. Also the logistic issues (e.g. does data downloading and battery replacement/charging can be done on the service vessel or the system has to be taken ashore?) will also influence the system design and functionality. Additionally, some systems are designed to transmit measured data to the external computer via some intermediate device. This is the most usually the buoy deployed (anchored) on the sea surface above the sea bottom mounted system. The data transmission from the measuring system to the buoy can be by the cable or by acoustic modem. The acoustic modem will, due to its restrictions, large amount of data and required data speed, require some kind of preprocessing to reduce the amount of data. The data link between the buoy and external computer placed somewhere ashore is usually done by radio or satellite data link. The data transmittion can be in the real time (without any storage in the bottom system) or employ some kind of intermittent or buffered scheme allowing the data to be recorded and then transmitted during the period when the measurement is not done.

In the acoustic sense, the hydrophone employed in the bottom mounted system has to record the direct sound (noise) only and to be clear of any significant reflections from the bottom, container and /or deployment gear. The geometry of the bottom mounted system including the deployment gear will depend on frequency range (wavelength) of the signal recorded, dimensions of the container and deployment gear and the bottom type. This has to be considered as early as in the design phase.

The bottom mounted systems for continuous underwater noise measurements will use deployment and recovery equipment that can include anchor, anchor line, acoustic releaser and flotation(s) as illustrated in Figure 3-2. The system container is packed together with flotation in the form of the collar around the container or flotation cylinders or spheres. This pack is hooked up to the anchor via acoustic releaser. The acoustic releaser is an oceanographic device used for the deployment and recovery of instrumentation from the sea floor, in which the recovery is triggered remotely by an acoustic command signal. A typical releaser consists of the hydrophone, the battery and the signal conditioning and processing electronics housing, and a hook which is opened to release the anchor by high-torque electrical motor. Each releaser has (or can be set to) unique acoustic command, and after receiving it, opens the hook and releases the measuring system and itself from the anchor. Owing to the flotation attached, the measuring system and releaser rises to the sea surface.

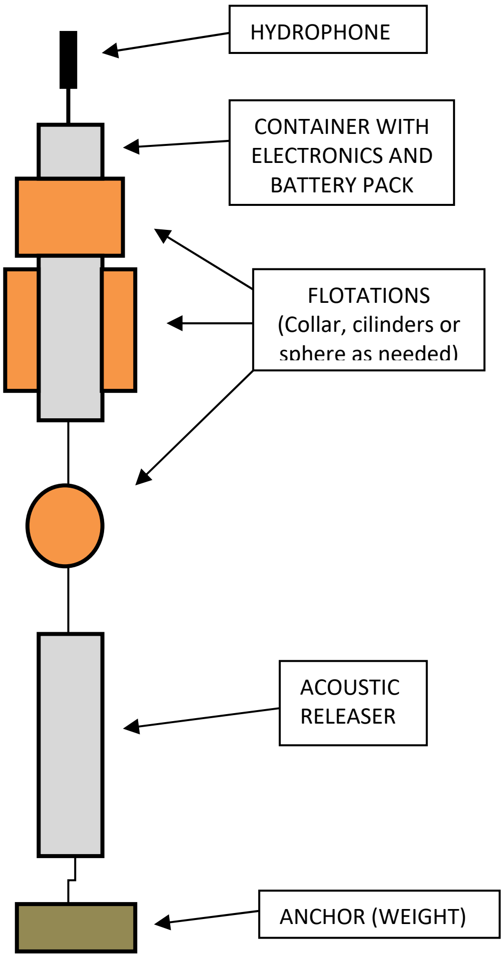


Figure 3-2 Continuous underwater noise measuring system setup using acoustic releaser for deployment

The alternative to acoustic releaser, but for the shallow deployments only, can be a diver who can release the measuring system from the anchor and let it surface owing to the flotation attached. The other alternative is to tie the bottom system to the surface buoy and to recover the system by the rope tied to the buoy as shown in Figure 3-3.

The anchor weight and shape are adjusted to the bottom type and expected strain to the system (e.g. currents or waves in case the surface buoy is used). If the bottom is mud, small and heavy anchor (e.g. lead) can gradually be buried into the bottom together with the measuring system thus compromising the part of the recording period and also causing problems with recovery. On the other hand, hard bottoms would ask for heavier anchors as the friction between anchor and the bottom is small. Anchor can be made in various shapes and material to best suit deployment procedures.

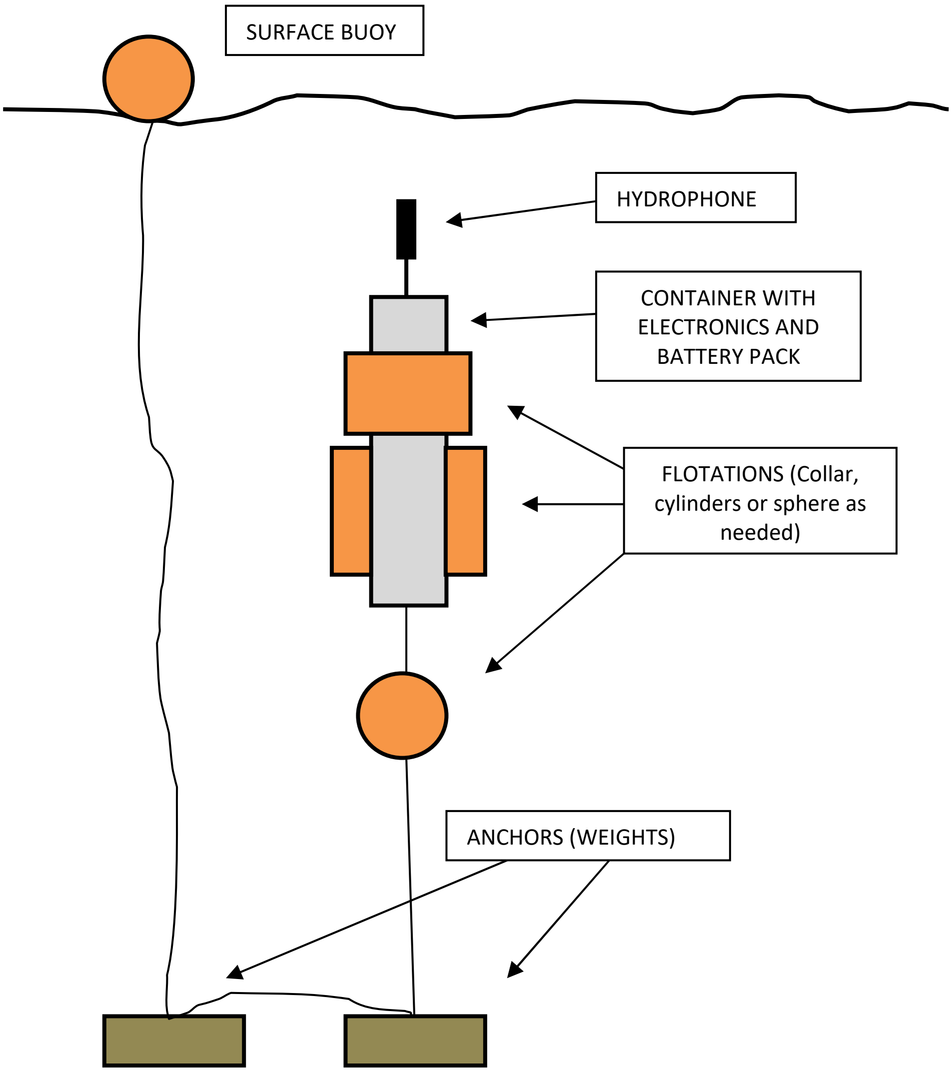


Figure 3-3 Continuous underwater noise measuring system setup using surface buoy for deployment

The anchor which is left on the sea floor can be environmentally unacceptable. Thus some systems employ the small container in which thin strong (e.g.kevlar) rope is winded and attached to the anchor with one end. After the system is released, the rope unwinds from the container and brings the other end on the surface. The anchor then can be lifted and used again. The alternative is not to use solid anchor (concrete, lead or iron) but to use biodegradable (e.g. juta) sacks filled with the sand or gravel. Such an anchor (or better to say deadweight) will remain on the sea bottom but will degrade and left only natural material (sand or gravel).

If the anchor weight/flotation ratio is carefully designed to achieve slow submersing, the whole system with deployment gear can be just slipped in the water from convenient vessel device (e.g. slipped with a slip hook from a A-frame, derrick or davit). In that case the impact of the system hitting the sea bottom will not damage the equipment. If this, for whatever reason, cannot be achieved, the system has to be lowered slowly to the bottom again using some convenient vessel device or diver assistance (e.g. with lift bag).

Due to the close proximity to the hydrophone, deployment gear can generate unwanted sound. This is especially true for the fixtures of the anchor rope to the anchor, acoustic releaser and system container, which are usually stainless steel shackles and eyes. Metal fixtures should be avoided or somehow isolated (e.g. rubber sleve) from the direct contact that can produce sound.

An important issue in the implementation of the bottom mounted systems is the maximum depth. While underwater housings can be made to withstand deeper deployments most commercially available hydrophones suitable for high quality underwater noise measurements have maximum depth specification in the range of hundreds meters, and only few of 1000 m.

Biofouling can also be an issue for longer deployments on some locations.

Bottom mounted system’s main advantages include:

- The minimized unwanted parasitic sounds (noise) caused by surface platform, water-air surface (wind, waves)
- Long deployment periods. With the technological advancement in memory and battery capacity, combined with suitable recording parameters and on-off recording schemes, deployment periods up to two years can be achieved.
- Independence of weather conditions and remote locations. The recording of the underwater noise data are performed regardless of the weather conditions. Also, data can be recorded from distant and remote locations as no connection with the shore, or attendance of the location is needed.
- Relatively simple and inexpensive implementation, especially in shallow and mid-shallow waters.

Bottom mounted system’s main shortcomings include:

- Off line operation. Data are available only after the deployment period. Incorrect and missing data as well as the functionality of the system cannot be checked during the deployment period.
- Possibility of the loss or damage of the equipment (and data) due to fishing and other sea going activities, mainly trawling. As the system is left unattended and unmarked on the bottom there is possibility to be trawled up or caught by fishing gear. Various protocols are in use, from announcing the position to the authorities and fishermen community to marking the position with the surface buoy equipped with light and radar reflector. Protective anti-trawling housings are also used with variable

success. The good alternative is to identify natural barriers to fishing (e.g., large outcrops or shipwrecks) and locations that fishermen avoid for the deployment locations.

- Not suitable for the location with strong current or tidal flows. Such flows can cause high levels of flow noise as the system hydrophone is stationary.

3.2.2 Drifting systems

In case of the drifting systems a generic continuous underwater noise measuring system is deployed suspended from the surface buoy that drifts freely driven by wind, waves, current or tide.

All system parts except the hydrophone are usually placed inside the buoy. The hydrophone is suspended from the surface buoy at the desired depth and connected to the buoy with a cable. However, configuration with all system parts within waterproof pressure housing which is also suspended from the buoy is also possible. The most important feature of the drifter design is the positioning of the hydrophone to be stationary to the body of the water moving horizontally. The drogue (e.g. sea anchor, “underwater parachute”) is used for that purpose. The drogue also decouples the motion of the surface buoy from the hydrophone. Figure 3-4 shows a typical configuration of the drifting continuous underwater noise measuring system.

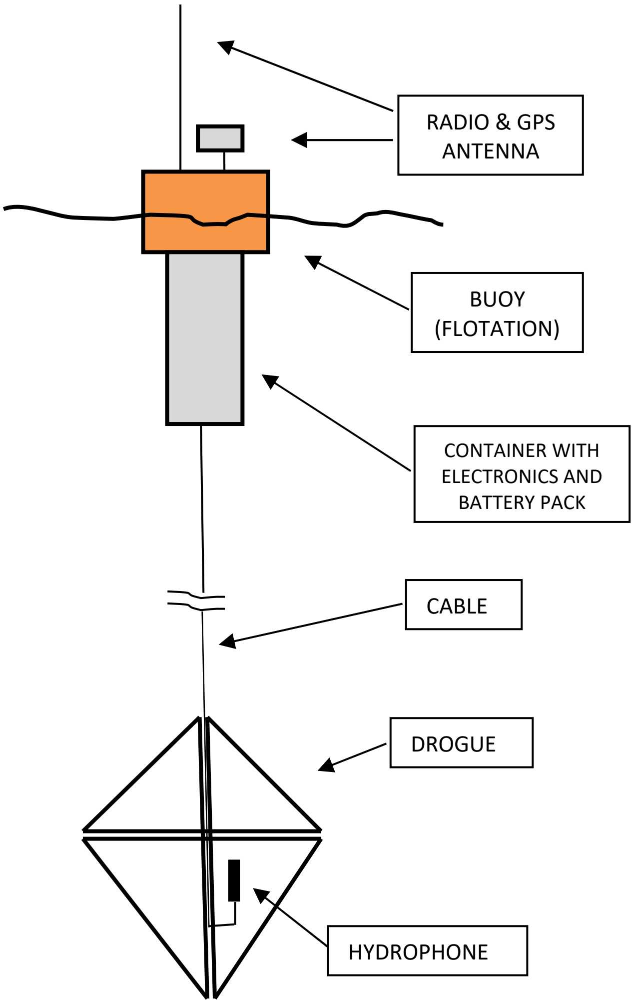


Figure 3-4 Typical configuration of the drifting continuous underwater noise measuring system

The most usual usage of the drifter methodology for continuous underwater noise measuring is the measurement of the underwater noise in strong current or tidal flows that would cause high levels of flow noise if the hydrophone of the system is stationary.

As the drifter is constantly moving, its exact position should be known in order to correctly process collected underwater noise data. Thus the GPS receiver on the buoy is the standard additional sensor and GPS position data are continuously logged. Measured underwater noise data can be stored in memory as is the case with bottom mounted systems and at the end of the deployment period downloaded to the external computer but can also be real-time (or near real-time) transmitted via radio or satellite data link.

The deployment and recovery of the drifter systems is relatively simple and inexpensive. As they do not employ any anchors, they are much lighter than bottom mounted systems and can be deployed from the smaller vessels and with less demanding gear. The recovery is simple as the buoy is lifted up from the surface with the rest of the system following.

The drifter systems also suffer from the possibility of the potential damage or theft. Unattended clearly visible and marked buoy can be vandalized or stolen by curious or malicious persons or crews.

Drifter system’s main advantages are:

- Suitability to measure underwater noise in strong flows avoiding the flow noise.
- Simple and inexpensive implementation

Drifter system’s main shortcomings are:

- More complicated processing and the analysis of the results due to its mobility
- Possibility of the loss or damage of the equipment

3.2.3 Surface based systems

In case of surface-based systems, a generic continuous underwater noise measuring system is deployed from a surface platform, most commonly a vessel. The vessel can be free floating, or more usually, anchored.

All system parts except the hydrophone are placed aboard the vessel, while the hydrophone is suspended from the vessel at the desired depth and connected to the equipment aboard with a cable.

The platform based underwater noise measuring systems are the most usual entry (starting) level for underwater noise measurements. The reason is that small vessels are easy to find and handled and the measuring equipment (amplifier, filter, A/D converter, etc.) can be easily-available general purpose laboratory equipment. Surface vessel based underwater noise measurement in shallow water not far from the coast is a relatively easy task. The great advantage of this methodology is that it is real time. The functionality of the system is always under control, measurement parameters can be adjusted and data monitored in real time. It can be very useful when starting to monitor underwater noise, when knowledge and experience are gained. Observed underwater noise signals can be directly linked to the events (e.g. vessel movements). Also, one can be sure that recordings are correct and there are no missing data, unlike the bottom-based system where missing data cannot be corrected.

The main drawback of such methodology is that surface vessel can (and in reality certainly is) the source of unwanted sound (platform self-noise) which is received and recorded by the hydrophone. All machinery and mechanical equipment on the vessel, as well as crew's activity onboard, vibrates the vessel's hull which produces underwater sound and that can be picked up by the hydrophone. Also, the hydrophone's cable and anchor chain strumming the vessel's hull and vessel splashing on the sea surface produces the underwater sound. Finally, any movement of the hydrophone caused by vessel movement (e.g. waves) to which it is connected, or pendulum like movement of the suspended hydrophone will produce flow noise. Avoiding platform self-noise is not an easy, sometimes impossible task. The most commonly used strategy is to suspend the hydrophone not directly from the vessel but from the buoy at some distance from the vessel, as shown in Figure 3-5. The hydrophone cable is connected from the hydrophone to the buoy and then horizontally to the vessel. In that way cable strum and the effect of vessel's movement can be reduced. Additional measures can be the strict control of the noisy activities onboard (engines shut down, crew's movement restricted etc.), if possible. For that reason, surface-based underwater noise measuring systems are not recommended for quality underwater noise measurements, unless the level of the platform self-noise is assessed and considered acceptable for the purpose of the measurement.

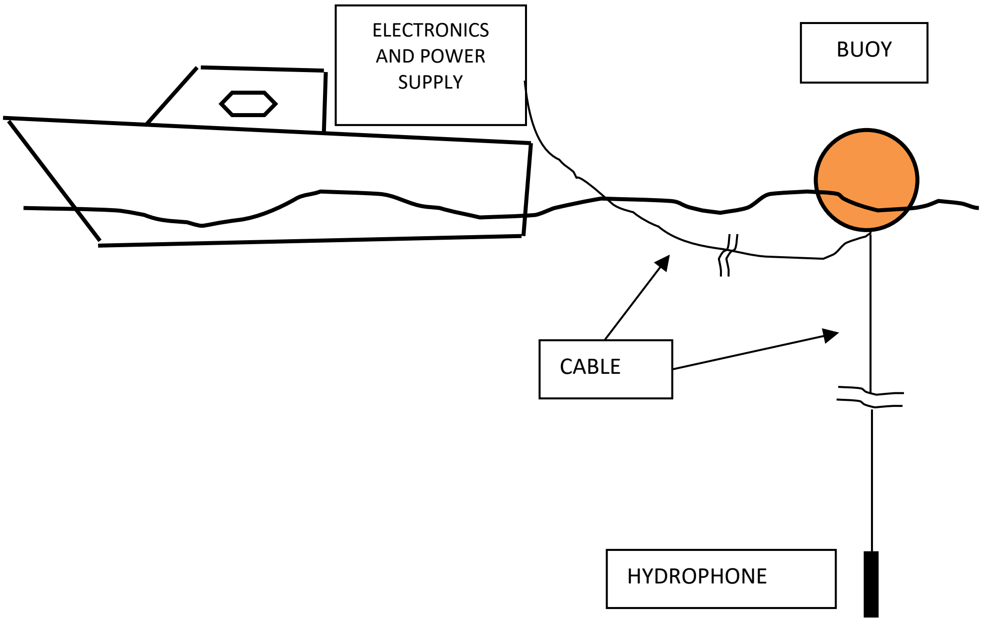


Figure 3-5 Surface platform based continuous underwater noise measuring system setup using auxiliary buoy for mitigating platform self noise

The deployment and recovery is very simple and easy, as only hydrophone, and where relevant the auxiliary buoy are deployed and recovered from the vessel. The cost of the deployment will depend of the size of the vessel used and the deployment time. Longer deployment times can be costly as the engagement of the vessel and the crew is usually charged by time. Unlike bottom-based systems where vessel is needed just for the short times of deployment and recovery, longer periods of vessel engagement will cost more. Also, longer deployment periods are greatly influenced by the weather conditions, as it can restrict vessel's stay on the location.

Platform-based underwater noise measuring systems do not suffer from the danger of equipment and data loss as it is attended and cared of during the entire deployment period.

Therefore, platform based underwater noise measuring systems can be recommended for short time, near shore shallow water underwater noise measurements where small boats can be employed and the platform self-noise can be maintained at an acceptable level.

The platform-based system's main advantages are:

- Relatively simple measurements possible with small boat and general purpose equipment (except the hydrophone)
- Real time measurements and recordings
- Easy deployment and recovery
- No danger of the loss or damage of the equipment and data.

The platform-based system's main drawbacks are:

- Platform induced parasitic (unwanted) sound (platform self-noise)
- Restricted operability due to weather conditions
- Increased cost for longer deployment periods

3.2.4 Land based systems

In case of the land based systems a generic continuous underwater noise measuring system is deployed on the land e.g. sea shore. All system parts except the hydrophone are located on land.

The hydrophone is placed on the sea bed and connected to the rest of the system equipment ashore with the long cable. The hydrophone usually contains the part of signal conditioning electronics allowing for use of long cables without signal quality loss. Besides connection for underwater noise signals, the cable provides power for the underwater parts of the system.

From a technical point of view, land based continuous underwater noise measuring system are close to the optimal system idea. This methodology is real time with all advantages as referred to in the section on surface platform-based systems. In addition, these systems do not suffer from potential lack of memory or power, deployment period is virtually indefinite, weather conditions on the hydrophone location are irrelevant, attending staff enjoy more safety and comfort while observing and/or processing recorded data.

The main and critical drawback of this methodology is the complex and potentially very expensive cable laying and connection to the land based equipment. This is the reason why this methodology was mainly used for military purposes (acoustic ranges). Recently this methodology was, or is planned to be, implemented for the relatively short distances from the shore. The other course is to include acoustic sensors to the more general or specific purpose sea observatories (e.g. seismic), thus reducing the cost of the deployment.

The sea bottom deployed hydrophone and long cables include potential risk of accidental damage by human, mostly fishing activities. But, as cable laying include compliance with legal regulations and various permits, it is possible that issue of the access to cable location could be regulated legally.

Biofouling of the hydrophone can also be an issue for longer deployments on some locations.

The land based system’s main advantages are:

- Real time operation
- Memory and power requirements are not an issue
- Deployment period virtually indefinite
- Weather conditions on the hydrophone location are irrelevant
- Low chance of equipment being stolen

The land based system’s main drawbacks are:

- The complex and expensive cable laying and connection to the land based equipment (but this can be compensated by near permanent deployment – all depends how long the monitoring programme is).

3.3 Hydrophones

A 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 sound and avoiding system overload at high sound levels. The recording of 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 criterion D11C2 are the two third-octave bands with nominal centre frequencies of 63 Hz and 125 Hz, it may be an advantage 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 criterion D11C2.

In that case 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, this occurs in the range of tens of kilohertz. If 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 a 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 $\mu Pa^2/Hz$ (or 1 $\mu Pa/\sqrt{Hz}$). The self-noise varies with acoustic frequency and as a result is usually presented as a noise spectral density level versus frequency. Self noise is an 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 sound 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. Low-noise hydrophones have 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 antropogenic noise, not to asses possible biological noise minima, the recommendation is that hydrophone self noise levels are below 53 dB re 1 $\mu Pa^2/Hz$ at 63 Hz and 49 dB re 1 $\mu Pa^2/Hz$ 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 $\mu Pa^2/Hz$ 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 high quality low-noise hydrophone have 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.

3.4 Measuring instrumentation

3.4.1 Front end electronics amplification (voltage gain) and filtering

Amplification (voltage gain) is the ratio of the input voltage signal from the hydrophone and the output signal from the front end electronics. The gain in the front end is useful to match existing hydrophone sensitivity with the sound levels expected and with the limitations arising from dynamic range of A/D converter. Weak signals (e.g. low sound pressure levels received with low sensitivity hydrophone) can decrease useful signal to noise ratio and too strong signal (e.g. high sound pressure levels received with a high sensitivity hydrophone) can overload A/D converter. Thus it is recommended that front electronic has the programmable or switchable voltage gain of 0 dB to 24 dB. The selection of gain can be in 3 or 6 dB steps.

The frequency range and self-noise of the front end electronics should match, and in no circumstances be inferior to the hydrophone frequency range and self-noise.

Filtering is the process of removing unwanted frequency components from the signal. In the measurement of the underwater sound, at the high end of the spectrum, the filtering is needed to avoid aliasing (low pass filtering). At the low end of the spectrum filtering is needed to avoid low frequency pressure variations not related to underwater sound but mainly to deployment related issues (high pass filtering). Low pass filtering is usually done in the A/D convertor according to its sampling settings.

High pass filter with the cut out frequencies of less than 10 Hz is recommended to filter out very low frequency signals which are generated by mechanisms such as surface motion and deployment method self noise. Such high pass filters can be incorporated in hydrophones which have internally built signal conditioning electronics.

3.4.2 A/D converter

Analog to digital converter (A/D converter) is an electronic device that takes a voltage source as an input, and yields a digital numerical output indicating the strength of the voltage at the source. The importance of the A/D converter in the measuring system is that it determines the dynamic range of the whole measuring system. The dynamic range of the measuring system is the amplitude range over which the system can accurately measure the sound pressure. This ranges from the self noise level of the system (which defines the lowest measurable signal) to the highest amplitude of signal that may be measured without overload or significant distortion. The dynamic range is expressed as the number of bits with which each sample is digitized. The number of bits per sample determines the quantization error, which should be lower than the lowest noise that one would like to analyse. The dynamic range should be chosen to be sufficient to enable the highest expected sound pressure level to be recorded accurately without overload or distortion and to prevent the lowest expected sound pressure level to suffer from quantification noise due to the poor resolution. The resolution of the A/D converter is recommended to be 24 bit if possible, but in no circumstances less than 16 bit. The dynamic range with 24 bit resolution will be 144 dB, while with 16 bit resolution 96 dB.

3.4.3 Data storage

The underwater noise data digitized in A/D converter will be stored in some kind of memory (most common memory card or disc). Although a number of suitable data formats exist, there is no standardized format for storing underwater noise data. To avoid degradation of the data quality, the data format used to store the data should be lossless (WAV or similar). The usage of compressed data formats (such as MP3) is not recommended.

Any crucial auxiliary data or metadata which is needed for interpretation of the results (e.g. the scale factor, gain or setting of the A/D converter) should be recorded. It is desirable that such information be included in a file header or log file so that the information is kept with the data.

The data storage used, should have enough memory space to store the planned duration of the measurement. The memory space needed is:

Sampling rate of A/D converter (in HZ) x Resolution of A/D converter (in byts) x Time of recording (in seconds)

If one wants to record with sampling rate of 24 kHz (24 000 Hz) and resolution of 24 bits (3 byte) continuously for 30 days (2 592 000 seconds) one would need 186 624 000 000 bytes or approx. 187 gigabyte of memory space.

3.5 Overall recommendations for the measuring system specifications

The whole measuring system should perform the following specifications:

- **Sensitivity**: The system sensitivity should be in the range from –165 dB re 1 V/µPa to –185 dB re 1 V/µPa.

- **Frequency range (Bandwidth)**: The system should have a flat frequency response (within ±1 dB) in the band from 5Hz-10kHz with the possibility of high pass filtering below 10 Hz.

- **Self-noise**: The whole system should have a maximum self-noise of **53 dB re 1 µPa2/Hz** at 63 Hz and **49 dB re 1 µPa2/Hz** at 125 Hz. For MSFD category B monitoring these requirements may be relaxed somewhat, but the self-noise should still be at least 6 dB below the lowest noise level of interest.

- **A/D Conversion**: Analog to digital converter should have resolution at least 16 bits (24 bits recommended) and at least 24 kHz sampling rate. A/D converter should have appropriate anti-aliasing filter.

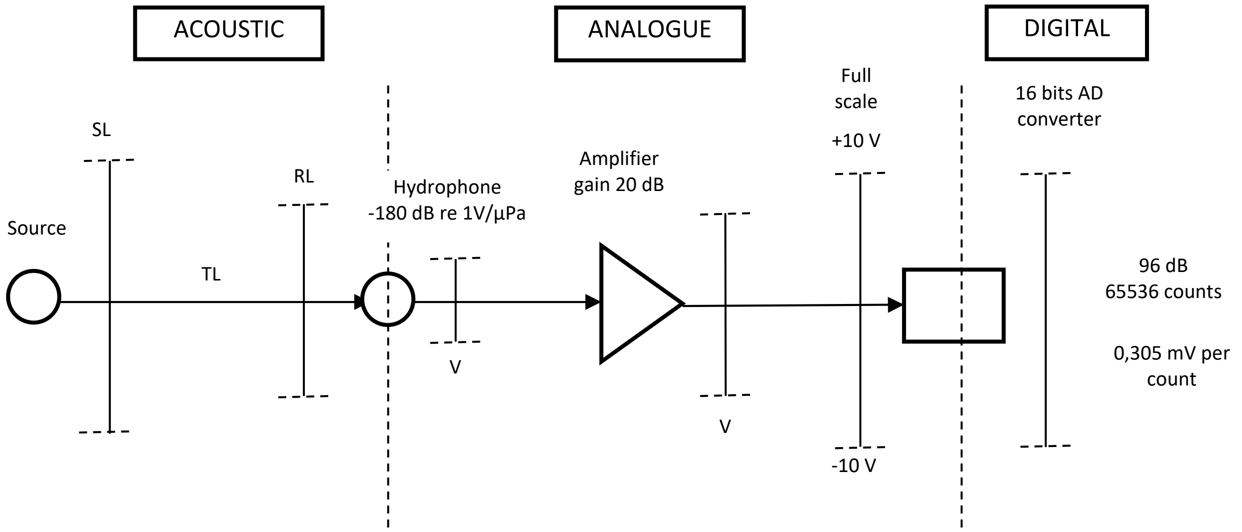
- **Data storage**: Storage capacity of the system should be at least 256 gigabyte

- **Batteries** : Battery life of the system must match planned duration of recordings with planned system settings.

- **Calibration**: The system has to be fully calibrated (hydrophone, amplifiers, filters, A/D converter,…) and the calibration documented.

- **Operational depth and temperature range** should match the planned deployment depth and temperature variations during the deployment.

It is very important to note that overall system performance will depend on matching of system sensitivity, gain and conversion resolution. Poor signal to noise ratios and system overload and distortion should be avoided. The overview of the signal levels in the generic continuous underwater noise measuring system is shown on Figure 3-6. The source radiates sound with source level SL. The sound travels to receiver and, after being attenuated which is represented by propagation loss (PL), is received with received sound pressure level RL. After being converted to voltage by the hydrophone and amplified, it is imputed to 16 bit A/D converter. The electronics are supplied with the supply voltage enabling ±10 V of amplifier dynamics and full scale of A/D converter. Three scenarios are shown in the table below. If source level is 230 dB re 1µPa m, A/D converter will output and record ±10360 counts which is near the middle of the dynamic range of amplifier and A/D converter. If the source level of the radiated sound increases to 250 dB re 1µPa m, the signal on the input of the amplifier will overload the amplifier, input to A/D converter will be clipped, and final result of the conversion incorrect. If the source level decreases to 170 dB re 1µPa m, AD converter will output only ±10 counts which is 0,015% of the available dynamic range, and therefore the signal will be hardly recognizable in the noise.



SL (dB re 1µPa m)	TL (dB)	RL (dBre 1µPa)	Hydrophone output / Amplifier input	Amplifier output / AD converter input	AD converter output
230	60	170	±316 mV	±3,16 V	± 10360 counts
250	60	190	±3,16 V	±31,6 V	clipped
170	60	110	±0,316 mV	±3,16 mV	± 10 counts

Figure 3-6 Overview of the signal levels in the generic continuous underwater noise measuring system

If one, for example, has to perform category B monitoring or similar, where proximity of strong underwater noise source levels are probable, it is recommended that system could withstand noise pressures (received levels) of at least 180 db re 1 µPa. If high sensitivity hydrophone (-165 dB re 1 V/µPa) is used, with no additional gain it will output voltage of 15 dB re 1V (approx 5.62 V). With realistic supply voltage it will probably not overload (but will be very close to the upper dynamic limit) the amplifier and converter and cause no significant distortion. However, in that case it is better to be on the safe side and use less sensitive hydrophone and certainly no gain.

On the other hand, if low noise levels are expected high sensitivity hydrophone will substantially increase signal to noise ratio.

It will greatly help to ensure the right system if, prior to specifying the system and deployment, even a rough estimate of noise levels expected is made.

The recommendation could be to use hydrophone with medium sensitivity (approx. -170 to -175 dB re 1 V/µPa) and to apply some level of voltage gain. That will give system certain flexibility to accommodate higher noise levels expected by decreasing applied gain.

If a high quality system (with self-noise and resolution as recommended) is used, probably 120 – 130 dB dynamic range will be sufficient. If not, the use of the measuring system with more than one channel is recommended. For each of the channels, the gain setting, the A/D converter scale setting and even the hydrophone can be chosen to match the expected sound pressure levels and achieve good quality data that is significantly above the self-noise floor but without distortion or saturation. A disadvantage is that the system is more complex, requires more calibration, and requires more complex processing.

3.6 Calibration

If one wants to perform underwater noise monitoring by the measurement of the absolute values of the pressure levels, the calibration of the entire measuring chain is the must. Calibration is the setting of a measuring device to match or conform to a dependably known and unvarying measure. Calibration will make measurement results comparable and trustable.

The system calibration can be undertaken either by full system calibration, or by calibration of individual components. For a full system calibration, the hydrophone is exposed to a known sound pressure field and recordings of the system output are analysed. For calibration of individual components, the hydrophone is calibrated separately by an acoustic measurement, but the other components are calibrated using known electrical input signals. The calibration is recommended to be performed by following internatinal standards and be traceable to national or international standards maintained at the national metrology institutions.

The detailed recommandations for continuous underwater noise measurement system calibration are presented in the document "*Best practices guidelines on sensor calibration for underwater noise monitoring in the Mediterranean Sea*".

3.7 Measurement uncertainties

When reporting the result of a measurement of a physical quantity, it is very important that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results are hard to compare. The concept of *uncertainty* as a quantifiable attribute is relatively new in the history of measurement but a worldwide consensus on the evaluation and expression of uncertainty in measurement permits the significance of a vast spectrum of measurement results to be readily understood and properly interpreted.

The uncertainty of measurement is defined as a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

The result of any quantitative measurement has two essential components:

- A numerical value which gives the best estimate of the quantity being measured (the measurand). This estimate may well be a single measurement or the mean value of a series of measurements.
- A measure of the uncertainty associated with this estimated value.

The concept of *uncertainty* is an attempt to quantify measurement accuracy without knowledge of the true value. An uncertainty provides bounds around the measured value within which it is believed that the true value lies, with a specified level of confidence. However, it is only possible to state the probability that the value lies within a given interval.

The uncertainty of the result of a measurement generally consists of several components. The components are regarded as random variables, and may be grouped into two categories according to the method used to estimate their numerical values:

Type A, which is method of evaluation of uncertainty by the statistical analysis of series of observations, and

Type B, which is method of evaluation of uncertainty by means other than the statistical analysis of series of observations. These may include:

- Information associated with an authoritative published numerical quantity
- Information associated with the numerical quantity of a certified reference material
- Data obtained from a calibration certificate
- Information obtained from limits deduced through personal experience
- Scientific judgment

The type A uncertainty (precision) corresponds to the previous classification of *random* uncertainty or *repeatability*, and may be assessed by making repeated measurements of a quantity and examining the statistical spread in the results. Type A uncertainty is a measure of the precision in the measurement, high precision is obtained if the measurements are repeatable with little dispersion in the results.

The type B uncertainty (bias) corresponds to the previous classification of *systematic* uncertainty and represents the potential for systematic bias in a measurement. This category of uncertainty cannot be assessed using repeated measurements and must be evaluated by consideration of the potential influencing factors on the measurement accuracy.

Any detailed report of the uncertainty should consist of a complete list of the components, specifying for each the method used to obtain its numerical value.

The combined uncertainty should be characterized by the numerical value obtained by applying the usual method for the combination of variances. The combined uncertainty and its components should be expressed in the form of “standard deviations”.

In practice, there are many possible sources of uncertainty in a measurement, including:

- incomplete definition of the measurand;
- imperfect realization of the definition of the measurand;
- nonrepresentative sampling — the sample measured may not represent the defined measurand;
- inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions;
- personal bias in reading analogue instruments;
- finite instrument resolution or discrimination threshold;
- inexact values of measurement standards and reference materials;
- inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm;
- approximations and assumptions incorporated in the measurement method and procedure;
- variations in repeated observations of the measurand under apparently identical conditions.

The results of the continuous underwater noise monitoring which are assessed by the measurement should consist of, as stated previously, numerical value which is the estimate of the measured noise level, and the measure of the uncertainty associated with this estimated value. The uncertainty components of the continuous underwater noise measurement would be of the type B uncertainty as continuous underwater noise is random process. Therefore, it makes no sense repeating measurements as the source levels during the new measurement will differ from the previous ones.

For assessing of measurement uncertainty, a complete list of all the components specifying for each the method used to obtain each numerical value should be produced.

There is a significant knowledge gap in definition and quantification of the uncertainty components of continuous underwater noise measurement. Therefore, only tentative possible sources of uncertainty in a measurement are proposed that may include some of the following.

Validity of any assumptions made. In designing, setting up and deploying continuous underwater noise measuring system, various assumptions are made e.g. assumptions of the acoustic field (free field, far field etc.). All assumptions made should be reconsidered and validated to mitigate possible uncertainties.

Equipment calibration. The calibration data will include uncertainty of calibration parameter e.g. hydrophone sensitivity or amplifier gain, and will contribute to the overall uncertainty. Good calibration laboratory traceable to appropriate standards can calibrate hydrophone with an uncertainty of less than 0.5 dB, and the overall uncertainty of the continuous underwater noise measuring system calibration can be of the order of 1 dB.

Temporal sampling of the continuous underwater noise. As mentioned before in section 4, 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. If this is the case, the average level of the recorded noise in the "on" period can differ from the average level that would be recorded if the recording was continuous over the whole period. The recorded level of the continuous underwater noise using intermittent (on-off) recording scheme will contain the uncertainty component due to the difference in recorded period averaged noise level to overall period averaged noise level. There are no scientific or engineering data of the possible quantity of this uncertainty component which represents another knowledge gap in the assessment of the overall measurement uncertainty. Nevertheless, as this component can be in some cases significant, this issue should be considered important to address in the future

Spatial position of the hydrophone. Depending on the measurement and/or deployment methodology the hydrophone will be placed on the different position in the water column. All reflective surfaces in the hydrophone's environment will theoretically affect reception of the direct noise signal. The reflected signal received by the hydrophone together with the direct signal would produce interferences and changes in the received noise level. Also, parts of the deployment gear (e.g. flotations) or the case containing batteries and electronics can add to the diffraction or the shadowing of the sound waves also affecting the received levels. The assessment of this component of the overall uncertainty is not an easy task as it is case (deployment) as well as frequency dependent. In the case of bottom based system where hydrophone can be very close (1-2 m) to the eventually hard bottom, reflections from the bottom will surely have not negligible effect on the levels recorded. Also, on the low frequencies where wavelengths are long (10 – 20 m) recorder casing or the flotations with typical dimensions of tens of centimeters will have minimal reflective or diffractive influence. There are no scientific or engineering data of the possible uncertainties caused by the hydrophone position in different deployment settings but as the illustration, Figure 3-7 shows the difference in sensitivity diagrams for the hydrophone close to the reflective surface (fixed) and away from it (cabled) in the case the sound incides from the direction parallel to the hydrophone.

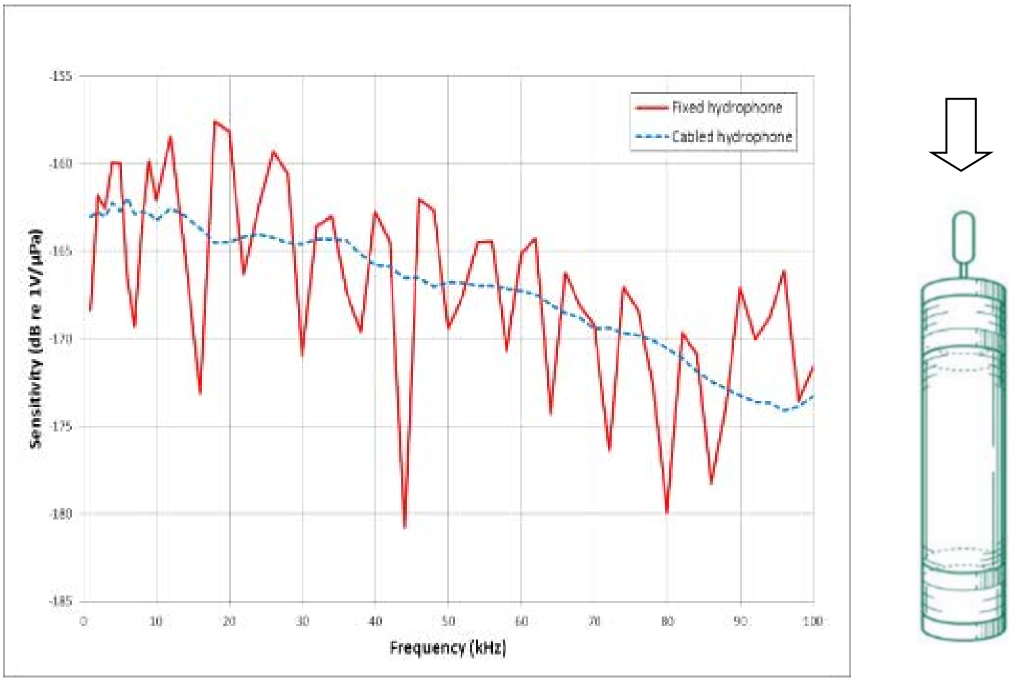


Figure 3-7 The difference in sensitivity diagrams for the hydrophone close to the reflective surface (fixed) and away from it (cabled)

It is obvious that broadband as well as one third octave measured levels will differ depending on the hydrophone placing.

Although there is substantial knowledge gap in determining this measurement uncertainity component, it is strongly recommended that additional effort should be devoted to this issue as it is evident that this component may seriously compromise the results of the measurement.

Platform and/or deployment induced (unwanted) sound. In spite of every attempt to eliminate sources of unwanted sounds caused by platform and/or deployment gear such are those identified in section 4.2, some residual effects will be present in some measurement methods. It is recommended that the levels of these unwanted sounds be assessed and checked against the lowest levels expected to be recorded. If level of unwanted sound caused by platform and/or deployment gear is well below the lowest levels expected, the contribution of this component to the overall measurement uncertainty can be very low and ignored.

Environmental parameters. Some parts of the measurement system, mostly hydrophone, can perform differently if environmental parameters differ from those encountered during calibration. The hydrophones are usually calibrated in calibration tanks at room temperature and in shallow water (low pressure). If this hydrophone is put in deep water (e.g. maximum rated depth) it will be exposed to much higher pressure and lower temperature than when calibrated. It can cause it to have a different sensitivity or frequency linearity. It is recommended that any change in any measurement system component specification be assessed if used in environmental parameters different to reference ones.

3.8 Data storage and handling

The whole process of measurement is designed to obtain data on levels of the underwater sound. A lot of effort and resources have been invested in getting those data. Therefore, the data should be considered precious and treated accordingly. Any compromise, corruption or even loss of data should be reduced to absolute minimum levels.

In case of autonomous measurement systems where the data are recorded on memory cards or solid state discs, the memory should be labelled, write protected and immediately backed up to a secondary device after its removal from the recorder. The quick quality check of the secondary copy is recommended while still in the field. At least the number and size of the files recorded should be checked, as well as does the start and stop time of the recording correspond to the real time when the recording was started and stopped. If something does not match, maybe there is possibility, while still in the field, to correct it (e.g. one forgot to take out one or more SD cards from the recorder). The primary (retrieved from the recorder) and secondary (on the secondary device) set of raw data should be packed and kept separately until brought to the laboratory. There, it is recommended to make another copy of the primary memory to have two separate backup copies of the original raw data sets. Also, it is recommended that different technologies be used for those copies. In today's state of the art one set will surely be recorded on magnetic discs while the other can be on the solid state disc, which today, although more expensive, matches magnetic discs in memory capacity. Never use those backup copies to work with. To ensure this, make these backups read only. For all work on further processing the raw data, make a working copy of the relevant file(s) from the backup copy and work with it.

The original (primary) memory should be kept at least to the moment the thorough quality check and/or pre-processing of the raw data is performed and the quality of the backup data is confirmed. If it is possible, it is recommended that the original (primary) memory be kept even after that, for a period of time considered appropriate.

The number of the auxiliary data (other than noise levels) should be also recorded and kept together with noise levels raw data to allow noise data to be, without ambiguity, linked to position, time period, type of equipment used, environmental conditions etc. Those data should be defined with the deployment protocol and may include name, geographic position and the depth of the measurement site, start and stop time for each recording, equipment type, serial number and set up data, calibration data, wind speed etc. One of the possibilities is to include those data in the header of raw noise level data files, thus keeping it together. If the separate file(s) are used, both raw noise level data file and file with auxiliary data should be labelled in ways to avoid any ambiguity. It is recommended that auxiliary data (or at least those crucial for the identification of the noise data file) be recorded while still in the field and included in the initial quick quality check. In that way one can be sure that raw noise level data file is correctly identified and attributed to the corresponding auxiliary data. It is self evident that each backup copy should contain all auxiliary data.

In case when measured data are not recorded in the measuring equipment but transmitted directly (e.g. by cable or radio) to an external computer for final storage and processing, the backup copies of the raw noise level data file should also be made. The measurement procedure should define a way of backing up the steady stream of the data. It may include parallel recording on two different secondary devices, serial protocol in which data from one secondary memory device are transferred automatically to the other or manual backup which would require data recording to be stopped for a short time to allow recorded data to be backed up. All other recommendations as for autonomous recorders should also apply for this case of data recording.

Annex I Acoustic quantities and metrics

When stating the results of acoustic measurements it is very important that the meaning of these results be transparent and unambiguous.

A number of different quantities and terms are used in relation to the metrics of the underwater noise mesurements. Only metrics and quantities necessery for the understanding of continuous underwater noise measurement are mentioned and defined here.

This section assumes a basic knowledge of acoustics or physics and does **not** attempt to provide a beginner's guide, nor a description from first principles. There are extensive literature covering that knowledge. Besides basic text books on acoustics and underwater acoustics, insight into several excellent references cited in the bibliography section is very instructive.

Sound pressure, *p* is the contribution to total pressure caused by the action of sound. Sound pressure is expressed in pascals (Pa)

Mean square sound pressure is the time integral of squared sound pressure over a specified time interval, divided by the duration of the time interval. Expressed in units of squared pascals (Pa^2).

$$\overline{p^2} = \frac{1}{T}\int_0^T p(t)^2 dt$$

Root mean square (RMS) sound pressure is the square root of the mean square sound pressure of the signal over a specific time interval:

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt}$$

The RMS sound pressure is calculated by first squaring the values of sound pressure, averaging over the specified time interval, and then taking the square root. The RMS sound pressure is expressed in pascals (Pa)

Reference sound pressure, p_0 is conventionally chosen and equals 1 µPa

The usual convention both in general and underwater acoustics is the use of **levels**. In its most general form, a level L_Q of a quantity Q is defined as the logarithm of the ratio of the quantity Q to its reference value, Q_0. In formula form, this definition can be written as

$$L_Q = \log_{\mathrm{r}} \frac{Q}{Q_0}$$

The nature of the quantity (Q), its reference value (Q_0) and the base of the logarithm (r) should all be specified.

Two types of level are in widespread use in underwater acoustics, the level of a field quantity and the level of a power quantity. In underwater acoustics, it is conventional to express both types of level in **decibels (dB)**.

When expressed in decibels, the level L_F of a field quantity F is

$$L_F = 20 \log_{10} \frac{F}{F_0}$$

where F_0 is the reference value of the field quantity.

Similarly, the level L_P of a power quantity P is

$$L_P = 10 \log_{10} \frac{P}{P_0}$$

where P_0 is the reference value of the power quantity.

This definition of L_P is a product of the three factors 10, $\log_{10}(P/P_0)$ and 1dB. In words, this product is written as "ten times the logarithm to the base 10 of the ratio P/P_0, in decibels". For levels of both field and power quantities, the nature of the quantity (F or P) is implied by the name of the level, while the base of the logarithm is implied by the use of decibel as the unit.

Sound Pressure Level (SPL), is a logarithmic measure of the mean square sound pressure

The sound pressure level (SPL) may be calculated as either:

(i) ten times the logarithm to base 10 of the ratio of the mean square sound pressure over a stated time interval to the reference value of sound pressure squared;

or

(ii) twenty times the logarithm to base 10 of the ratio of the root mean square sound pressure over a stated time interval to the reference value for sound pressure.

The two definitions are mathematically identical, as may be seen from the following expression:

$$SPL = 10\ log\ \frac{\frac{1}{T}\int_0^T p(t)^2 dt}{p_0^2} = 10\ \ log\ \frac{\overline{p^2}}{p_0^2} = \ 20\ log\ \frac{\sqrt{\frac{1}{T}\int_0^T p(t)^2 dt}}{p_0} = 20\ log\ \frac{p_{rms}}{p_0}$$

Although the two expressions for sound pressure level are mathematically identical, they are sometimes referred to as "mean-square-sound-pressure level" and "root-mean-square-sound-pressure level" to distinguish them. When using mean-square-sound-pressure level, the reference value is stated as 1 μPa^2, leading to mean-square-sound-pressure level being expressed in units of dB re 1 μPa^2.

The time interval used in the calculation of SPL **must** be stated. Also, if any frequency weighting is applied it should be stated that calculated sound pressure level is weighted and denoted as SPL$_W$.

Note that sometimes the quantity **equivalent sound level *L_{eq}*** , analogue to air acoustics, is used.

$$L_{eq,T} = 10\ log\ \frac{\frac{1}{T}\int_0^T p^2(t)dt}{{p_0}^2}$$

Although strictly in theory it is not identical to SPL as defined above, in practice it yields the same results providing that the same reference and averaging time interval are used.

The recommended metric which is considered the most suitable for continuous underwater noise is **Sound Pressure Level (SPL).**

Annex II Shallow water specific environmental dependence and cut-off frequency

When considering underwater sound propagation models, one effect not always appreciated is that shallow water channels do not allow the propagation of low frequency signals due to the wave-guide effect of the channel. This effect means that there will be a lower cut-off frequency, below which sound waves will hardly propagate in the water column, but will be radiated into the sea-bed instead. In this case propagation in the water column is poor and the acoustic field decreases rapidly with range.

Shallow water channel cut-off frequency can be explained and predicted by a normal mode analysis. This is complex problem which involves entire system of sound frequency, source/receiver depths and environmental parameters (water column, bottom).

However, for a realistic seabed, a simplified formula for the assessment of cut-off frequency depending on the ratio of sound speed in the bottom to that in the water can be used.

$$f_0 = \frac{c_w}{4 \cdot D\sqrt{1-(c_w/c_b)^2}}$$

where D is the water depth, c_w is the sound speed in the water and c_b is the sound speed in the sea-bed.

The expression is valid only for homogeneous water column depth D. The result of plotting this formula is shown in Figure AII-1. The sound speed in water is assumed to be 1490 m/s while sound speed in water to be 1700 m/s.

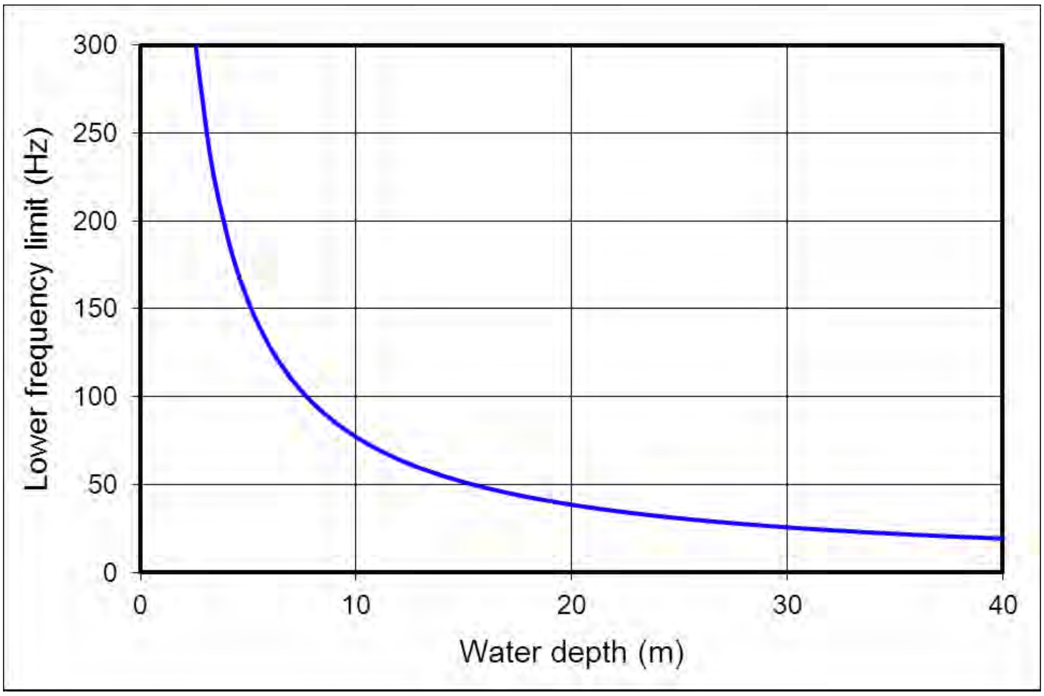


Figure AII-1 The lower cut-off frequency as a function of depth for a shallow water channel

From Figure AII-1 one can see that, for example, frequencies below around 80 Hz would not be expected to propagate through the water in an approximate water depth of 10 m.