Joint Monitoring Programme for Ambient Noise North Sea

2018 – 2020

Standard procedure for equipment performance, calibration and deployment

WP 3

Deliverable/Task: 3.2

Authors: N. Crawford, S Robinson, L. Wang.

Affiliations: NPL

Date: August 2018

Project Full Title	Joint Monitoring Programme for Ambient Noise North Sea
Project Acronym	Jomopans
Programme	Interreg North Region Programme
Programme Priority	Priority 3 Sustainable North Sea Region

Colophon

Authors	N. Crawford, S Robinson, L. Wang.
Organization Name	NPL
Email	stephen.robinson@npl.co.uk
Phone	+44 20 8943 7152

Version	Date	Review	Initial	Approval	Initial
1.0	Aug 2018			Kinneging	

This report should be cited:

Crawford, N., Robinson, S. and Wang, L. (2018) *Standard procedure for equipment performance, calibration and deployment*. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (Jomopans), August 2018

Cover picture: NPL, © Crown Copyright

Table of contents

Summary

This report is a Deliverable 3.2 of Work Package 3 of project JOMOPANS.

The aim of WP3 is to develop underwater noise monitoring standards suitable for monitoring MSFD Indicator 11.2.1 in the North Sea Region as part of "JOMOPANS" joint monitoring project.

At this moment, there are no international standards for monitoring and mapping ambient noise in the ocean. Such standards would require consensus on a number of topics:

(i) Terminology for describing the monitoring of underwater ambient noise;
(ii) Specification, performance requirements, calibration and deployment of the measurement equipment;
(iii) Analysis of the measured data obtained from monitoring;
(iv) Acoustic modelling of underwater sound field.

Within the project, there is a need to standardize these activities so that all partners use a common approach in order that data obtained within the project are comparable.

Task 3.2 is concerned with developing a standard for equipment performance, calibration and deployment as in item (ii) above.

This task involves three sub-tasks:

3.2.1 Specification of required equipment performance

Key equipment parameters to be specified include frequency range, dynamic range, sensitivity, directionality, sampling rate, filtering, system self-noise.

3.2.2 Specification of calibration requirements for instrumentation

Calibration requirements for instrumentation will include calibration methodology, traceability to international standards, specification of measurements required, frequency range, and uncertainty requirements. In-situ calibration checks undertaken before and after deployment will also be covered.
Note that WP3 will provide guidance on calibration of instrumentation, but resourcing and undertaking the calibration of instrumentation is the responsibility of those partners carrying out the measurements in WP5.

3.2.3 Specification of deployment methodology

Specification of recommended methodology for deployment, including rigging and anchoring will be given. Recommendations will also be made for methods to mitigate the influence of parasitic signals caused by contaminating artefacts such as cable strum, and flow noise, etc. Procedures will be recommended for quality assurance when retrieving and storing data. Recommendations will be made for measurement and recording of auxiliary data, for example, wind speed, water depth, air temperature, GPS location, seabed type, etc.

Throughout the course of compiling this document, a number of procedural documents from previous studies have been regularly referenced to ensure compliance including; Good Practice Guide for Underwater Noise Measurement **[1]**, BIAS standards for Noise Measurements **[2]**, UNAC-LOW Underwater Acoustic Calibration Standards for Frequencies Below 1kHz **[3]**, and ADEON Underwater Soundscape and Modelling Metadata Standard **[4]**.

Also a number of international standards have been utilised including; IEC 60565-1 CD **[5]**, IEC 60565-2 CDV **[6]**, IEC 612260-1:2014 **[7]**, ISO 18406:2017 **[8]**, and EU TSG 2014b **[9]**

1 Specification of required equipment performance

1.1 Choice of instrumentation

Within the project, there has been no attempt to standardise the instrumentation used for measuring ocean sound (as was the case for example in the BIAS project **[2]**). Standardising the instrumentation has advantages in that all partners will adopt common hardware, which has the potential to increase the comparability between the measured results. However, choosing one set of instrumentation has some disadvantages (as was evident in the BIAS project). Firstly, all the measurements may then be limited by the performance characteristics of the chosen instruments (which may or may not be the highest quality specification). Secondly, allowing partners to choose their own instrumentation enables both the use of existing legacy systems owned by partners (for cost efficiency), and allows those partners able to acquire new equipment to do so. So long as a minimum specification is achieved, the variety of equipment chosen will militate against any bias caused by the equipment choice.

In the JOMOPANS project, at least five of the final monitoring stations are planned to be systems hard-cabled to a shore base, enabling continuous sound monitoring. This has potential for a significant improvement over other similar projects utilising only autonomous recorders (eg more extensive temporal sampling). Other monitoring stations will utilise a number of different autonomous recorders operating at a variety of duty cycles. This means that this standard procedure cannot be too prescriptive in the guidance on equipment specification and deployment because the guidance must cover the use of the variety of chosen monitoring systems.

1.2 Recommended minimum performance specification

Table 1.1 Agreed minimum specification for equipment

Metric	**Specification**
Frequency range:	Nominally: 10 Hz – 20 kHz Note that to fully record the 34 third-octave bands in this frequency range requires measurement over the range 8.91 Hz to 22.39 kHz. Note: MSFD focus frequencies of interest are the 63 Hz and 125 Hz third-octave bands.
Dynamic range:	Minimum 16 bit (nominal dynamic range 96 dB), Preferably 24 bit (nominal dynamic range 144 dB) Note: actual dynamic range is from noise floor defined by system self-noise to the maximum measureable undistorted sound pressure
Sensitivity:	Ideally in the range: -165 to -185 dB re. 1 V/µPa
Frequency response	Ideally invariant with frequency (flat response) in the range 10 Hz to 20 kHz Note: see description of recorder performance when hydrophone is rigidly attached to body.
Directionality:	Omnidirectional to within +/- 1 dB up to 20 kHz azimuthal, and to within +/- 2 dB in vertical elevation Note: see description of recorder performance when hydrophone is rigidly attached to body
Sampling rate:	Minimum of 44 kHz Ideally at least 48 kHz (to capture upper band limit of 22.39 kHz for the 20 kHz third-octave band)
Filtering:	Any filter characteristics should be known and corrections applied (low pass and high pass filtering caused by instrumentation) Note: any low frequency roll-off in recorder performance due to high pass electronic filtering must be measured so that suitable corrections can be applied.
System self-noise:	Ideally, better than 64 dB re 1 μPa^2/Hz at 63 Hz; Ideally, better than 59 dB re 1 μPa^2/Hz at 125 Hz. Ideally, 6 dB below the lowest sound level. Note: the self-noise of some of legacy instrumentation used in the project (such as autonomous recorders) may not meet this specification.

1.3 Key performance characteristics

This section of the report explains in more detail what is meant by each metric identified in Table 1 as well as why these are important.

1.3.1 Instrumentation required

The measuring system will generally consist of the following instruments:

- Hydrophone(s);
- Amplifier(s) and signal conditioning equipment, such as filters;
- Digitisation and storage equipment;

The amplifier can be a separate element in the system with an adjustable gain, or may be an integral part of the hydrophone with no possibility for gain adjustment. Digitization is provided by an analogue to digital converter (ADC) and the electronic storage is typically provided by a computer hard drive or flash drive memory. **[1, 7]**

The measuring system may consist of individual components, as listed above, or an integrated system forming part of an autonomous recorder that provides a self-contained recording system. Below outlines some of these components and their respective roles within the system.

Hydrophones

Hydrophones are device that detect changes in pressure in the surrounding medium. A hydrophone will convert these pressure changes into an electrical voltage signal, which will then be passed on to other components of the system. Hydrophone calibration data is typically expressed in µV/Pa, or in decibels as dB re 1 V/µPa. Typically, it is expressed at a succession of discrete frequencies, or in the form of a calibration curve. **[1, 2]**

Amplifiers

The role of an amplifier is to increase the amplitude of signals so that the signals can reach levels appropriate for the next processing stages. The performance is typically expressed as a gain factor, either in terms of a linear gain (e.g. x10) or in decibels (e.g. 20 dB). Note that the amplifier gain may not be invariant with frequency, particularly at the extremes of the operating frequency band. **[1]**

Filters

A filter sets a range of which frequencies of a signal can pass through to the rest of the system and blocking frequencies outside of this range from passing. Filters are typically known as low pass, high pass or bandpass depending on their frequency response. The filter performance is typically expressed as an insertion loss factor, a positive number expressed either as a linear factor or in decibels. By definition, a filter response varies with frequency, and must be characterised over the full operating frequency range of the system.

Analogue to Digital Converter (ADC)

An ADC is used to convert a raw signal (analogue) into a useful format type (digital) to be processed / read by other components of the system analysing the signal. The range setting (full-scale) and the calibration factor of the ADC must be known. This is normally expressed as a scale factor, which will depend on the digital amplitude output values (counts) of the ADC for a stated input voltage, and is typically expressed as counts per volt. Note that this is not the same as the number of bits of the ADC **[1-4]**

Data storage

To avoid degradation of the data quality, the data format used to store the data should ideally be lossless (no data compression). If data compression formats are used in order to increase the storage capacity (and thereby the recording duration), the effect on the data quality should be known **[1].**

Any crucial auxiliary data or metadata that are needed for interpretation of the results should be recorded (for example, the scale factor or setting of the ADC, or the gains of any amplifiers, the sampling frequency and the resolution) **[1]**.

It is desirable that such calibration data information be included in a file header or log file so that the information is kept with the data. Without this information, the data file may essentially be "uncalibrated". Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data **[1, 8].**

If data storage is required to be long-term (many years), consideration should be given to the likely future compatibility of the storage media and data format. Note that some formats and storage media may become obsolete over time **[1]**.

1.3.2 Frequency range, frequency response and sampling

The frequency range over which measurements are made will usually depend on the objective of the measurements. For example, monitoring the potential impact on marine species, the frequency range of hearing of the marine receptors may govern the frequency range of the measurements **[1, 9]**. For the hydrophone being used, the lower frequency limit (10 Hz) may be the most difficult frequency to measure. So the hydrophone must be selected appropriately to enable all frequency components of interest to be recorded accurately. In JOMOPANS, the nominal frequency range is 10 Hz to 20 kHz, but the applicable frequency range is in fact 8.9 Hz to 22.3 kHz in order to cover the outer limits of the requisite third-octave bands.

The frequency response of the measuring system is the sensitivity as a function of acoustic frequency, and it is desirable for this response to extend to a high enough frequency to reliably record all frequency components of interest within the measured signal. This requires that any hydrophone, amplifier and filter, be sufficiently broadband **[7]**.

Sampling shall be selected within the desired frequency range. It is required the sampling rate of the ADC within the recording system to be greater than the Nyquist rate of the input signal, to avoid loss of information. **[1, 4]**

1.3.3 Dynamic range

The dynamic range of the measurement system is described as the amplitude range over which the system can faithfully measure the sound pressure **[7]**. The dynamic range of the measurement system will range from the lowest possible level of signal that can be measured (dictated by the 'self-noise' or 'noise floor' of the system), to the highest amplitude of signal that may be measured without distortion.

As this study looks at the low ambient noise levels, the measurement system is not expected to *routinely* experience high amplitude sound levels such as those that would be obtained from sources such as marine piling operations or airguns at close range. Due to this fact the self-noise / noise floor of the selected system should be considered more important than the ability of the system to record very high amplitude signals. As such, an appropriate hydrophone selection would be one with a built in low-noise preamplifier and high sensitivity in the frequency range 10 Hz to 20 kHz.

When measuring low amplitude signals, care is required to ensure that not only will the signal amplitude exceed the noise floor of the system, but also that the recorded signal is not so low as to suffer from quantisation noise due to the poor resolution of the ADC for very small signals. The resolution of the ADC should be at least 16-bit (some are now available at 24 or even 32 bits). With the use of modern high-resolution ADCs this is less of a problem than in the past. However, the system settings should be chosen to achieve recorded signals of appropriate resolution**.**

NOTE: The measuring system is required to be linear over the full dynamic range. This means that the system sensitivity is constant over the full range of measurable sound pressure. For some systems, when approaching the high amplitude limit, the response may no longer be linear due to limits in the performance of components such as amplifiers. Therefore, it is advisable that a measurement system is not used close to the limit of its dynamic range unless the linearity has been checked **[1].**

A method to mitigate problems with dynamic range is to have some flexibility in the sensitivity, often achieved by use of adjustable gains for amplifier stages and scale settings on ADCs. However, where a system has been deployed remotely (for example, an autonomous recording system which is left in-situ for an extended period), there may be no control over the system settings after deployment. Also, hydrophones with integral preamplifiers typically provide no control of preamplifier gain and will require substitution with another device if the gain is unsuited to the acoustic levels being measured (for example if saturation or clipping has occurred). In this case, some knowledge of the likely range of sound pressure levels is required to optimise the available dynamic range (this knowledge can be obtained from reported levels in the scientific literature or from approximate theoretical calculations).

Another issue that may cause difficulty when measuring broadband signals is that the amplitudes of the frequency components can vary over several orders of magnitude. For example, this can be a problem when measuring ambient noise where the low frequency components (eg at a few hundred hertz) may be much higher amplitude than the high frequency components (at tens of kilohertz). One method to overcome this problem is to use a measuring system which consists of several channels, each of which is used to measure a specific frequency band **[10]**. For each of the frequency bands, the amplifier gain setting, the ADC scale setting and even the hydrophone can be chosen to match the expected sound pressure levels and achieve good quality data that are significantly in excess of the noise floor but without distortion or saturation. The frequency bands must overlap if a continuous spectrum is to be recorded. A disadvantage of this approach is that the system is far more complex, requires more calibration, and requires processing such that the data for each frequency band are combined to form an overall spectrum. In addition, if two hydrophones are used, it is not possible to co-locate them, which means that the acoustic field will be sampled in two different positions (potentially important only at higher frequencies than are of interest in JOMOPANS) **[1]**.

1.3.4 Sensitivity

The sensitivity of the hydrophone shall be uniform over the stated frequency range, with a tolerance stated alongside. Ideally, the hydrophone and measuring system should be chosen to meet an appropriate sensitivity value for the amplitude of the sound being measured.

The aim in the choice of the system sensitivity is to:

- adequately sample low amplitude signals;
- avoid nonlinearity, clipping and system saturation for high amplitude signals.

The sensitivity of the entire measuring system must be known if absolute measurements of the sound field are required, and this will require a calibration. This includes the sensitivity of hydrophones, the gain of any amplifiers, filters and ADC's present in the instrument chain. The sensitivity is described in terms of the electrical voltage developed per pascal of acoustic pressure, and is stated in units of V/Pa (or, using units more appropriate for a typical sensitivity magnitude, in µV/Pa). The sensitivity level is often expressed in decibels as dB re 1 V/µPa. Note that the choice of a 1 V/µPa as the reference value leads to hydrophone sensitivity levels having very large negative values (for example: 56 µV/Pa is equivalent to -205 dB re 1 V/µPa) **[1].** For JOMOPANS, the desired system sensitivity is ideally in the range: -165 to -185 dB re. 1 V/µPa.

1.3.5 Directionality

Ideally, a hydrophone would have an omnidirectional response such that its sensitivity is invariant with the direction of the incoming sound wave. However, omni-directionality is only an approximation valid at low frequencies, where the hydrophone size is smaller to the acoustic wavelength. When the hydrophone size is comparable to or greater than the acoustic wavelength, the hydrophone will exhibit a directionality response **[1]**.

The hydrophone used shall have an omnidirectional response such that its sensitivity is invariant with the direction of the incoming sound wave to within a tolerance of 2 dB over the frequency range of interest.

NOTE: This requirement is not difficult to satisfy at frequencies up to 20 kHz. However, one issue that can cause enhanced directionality is where the hydrophone is deployed close to another structure that is capable of reflecting the sound waves. The combination of the direct and reflected waves causes interference, the nature of which will change depending on the frequency and arrival angle for the sound wave. This effect can be evident at kilohertz frequencies if the hydrophone is deployed close to a support structure such as a heavy mooring or support, or a recorder case that houses electronics and batteries but is mostly air-filled. Similarly, if the hydrophone has a guard deployed around it (a protective cage to prevent damage of the element by impacts), this can influence the directivity at kilohertz frequencies. If necessary, the above effects can be quantified by directional response measurements of the hydrophone together with the mounting, in a free-field environment **[7]**.

Usually, the directional response of the hydrophone is stated at the four highest preferred frequencies of the specified frequency range. The directional response close to the fundamental resonance shall also be stated if this resonance is inside the claimed operating frequency band. The method used to determine the directional response shall be stated. Each of the resulting directional responses obtained from the measurements shall also be stated.

1.3.6 Sampling rate

When sampling signals it is important to make sure data is represented in an unambiguous manner for the desired frequency range. This will require a sampling frequency equal to or greater than two times the maximum acoustic frequency recorded, (commonly known as the Nyquist frequency). The sampling is typically carried out through the systems ADC's components. It is common for systems to oversample such that the sampling frequency exceeds the minimum required (it is rare for systems to offer full frequency coverage up to the Nyquist frequency). It is advisable to use an anti-aliasing filter to avoid ambiguous representation of frequency content. Where the measured data are to be represented in third-octave bands, the maximum frequency of interest will be the upper limit of the maximum third-octave frequency band of interest **[1, 7]**. For JOMOPANS, a sampling rate of a minimum of 44 kHz will be used, but ideally of at least 48 kHz (to capture upper band limit of 22.39 kHz for the 20 kHz third-octave band).

1.3.7 Filtering

The filtering equipment required in the instrumentation shall be able to set appropriate thresholds where frequencies outside the specified required band / bandwidth shall be removed. The filter types used in the instrumentation can range from low pass, high pass and bandpass filters. The performance of a filter's response will vary with frequency and so must be characterised over the full operating frequency range of the system. Typically this performance can be expressed as an insertion loss factor, a positive number expressed as either a linear factor or in decibels. Some commercial hydrophones integral preamplifiers are designed with a high pass filter to remove frequencies of less than 10 Hz to minimise influence of very low frequency parasitic signals typically generated by surface wave motion **[1, 4, 6]**

1.3.8 System self-noise

The system self-noise, sometimes referred to as the measurement systems "noise floor", is a crucial parameter when measuring low levels of sound, and governs the minimum sound be measured by the system **[1].**

The contaminating noise within the measuring system arises from two sources:

- noise generated by the hydrophone and recording system;
- noise generated by the deployment platform or mooring.

The system self-noise is considered to be the noise originating from the hydrophone and recording system. The system self-noise is the noise generated by the system in the absence of any signal due to an external acoustic stimulus. This noise is electrical in nature, and is generated by the hydrophone itself and any electronic components such as amplifiers and ADCs. This is normally expressed as a noise-equivalent sound pressure level in dB re 1 $\mu Pa^2/Hz$ **[5, 11]**. The system self-noise varies with frequency and as a result is typically presented as a noise spectral density level versus frequency.

The noise equivalent pressure may be calculated by measuring the system electrical noise and dividing by the system sensitivity, where the measurement is made without any external acoustic stimulus present. Note that although the system self-noise may be expressed in terms of a noise equivalent sound pressure level, the origin of the noise is purely electrical (from the hydrophone, amplifier and electronic components).

To achieve acceptable signal-to-noise ratio when measuring acoustic signals, the self-noise equivalent sound pressure level should ideally be at least 6 dB below the lowest noise level to be measured in the frequency range of interest. It is common to compare values for system self-noise with classic empirical curves for ambient noise levels in the ocean, such as those of Wenz **[12]** and Knudsen **[13]**.

.

2 Calibration requirements for instrumentation

2.1 Aims

Calibration requirements for instrumentation will include calibration methodology, traceability to international standards, specification of measurement required, frequency range, and uncertainty requirements. In-situ calibration checks undertaken before and after deployment will also be covered.

Note that WP3 will provide guidance on calibration of instrumentation, but resourcing and undertaking the calibration of instrumentation is the responsibility of those partners carrying out the measurements in WP5.

2.2 Calibration requirements

The total components that require calibration are as follows:

- Hydrophone / Recorders
- Amplifiers
- Filters
- Analogue to digital converter (ADC) (provided with range setting and calibration factor)

A laboratory calibration requires that the system undergo a series of measurements to determine the sensitivity. It is very risky to rely on indicative or nominal calibration values produced at the system design stage, and this is not recommended. The calibration should cover the full frequency range of interest for the specific application at hand. For example it is possible to calibrate a hydrophone and recording system with an overall uncertainty of better than 1 dB (expressed at a 95% confidence level). It is recommended that a full laboratory calibration is undertaken before and after every major deployment or sea-trial **[1, 5, 11].**

In JOMOPANS, all measuring instrumentation must be calibrated traceable to national or international standards.

2.3 Low frequency pressure calibration methods

There are a number of ways to calibrate a hydrophone via a low frequency pressure calibration which are described below.

2.3.1 Pistonphone

This calibration method only applies to frequencies ranging from a few hertz to several hundred hertz. The method itself is completed by inserting the hydrophone into a closed chamber filled with air. The end-of-cable pressure sensitivity of a hydrophone can then be determined by simultaneously exposing the hydrophone and a calibrated microphone to the sinusoidal pressure field in the above described ‘small sealed enclosure’

More information on this calibration method is provided in the IEC document **[5]**

2.3.2 Vibrating column

This calibration method only apply to a frequency range of 10 Hz to 2 kHz. The hydrophone is placed in an open chamber which must have a larger wavelength than the length of the column. The hydrophone is placed in a column of liquid (suspended in a fixed vertical position near to the central axis of the column) which is then vibrated by either an electrodynamic transducer or a vibrating generator. The sensitivity of the hydrophone will be obtained from the calculated pressure at the depth of the hydrophone and the measured open-circuit voltage.

More information on this calibration method is provided in the IEC document **[5]**

2.4 Free field calibration methods

Free-field calibration is measurement of the response of the sensor to a plane wave incident from a given direction. There are two commonly used methods for free field hydrophone calibration which are described below:

2.4.1 Reciprocity-based method

The end-of-cable open-circuit free-field receive sensitivity of the hydrophone can be determined by the method of three-transducer spherical-wave reciprocity in conformance with international standards **[5].** This procedure requires that three hydrophones be operated in pairs, with one transmitting and one receiving. The three devices will normally be labelled P (projector), H (hydrophone), and T (reciprocal transducer). This calibration and at least one of the devices must be reciprocal **[1]**.

In each case, using one device as a projector and the other as a hydrophone, the electrical transfer impedance shall be determined at the desired number of frequencies throughout the frequency range of interest. Using at least the first three configurations of transducer pairs, the free-field receive sensitivity and transmitting response to current of any of the three devices is calculated at each frequency of calibration from the measurements of purely electrical quantities (transfer impedances), the separation distance, and the water density and acoustic frequency. If the projector, P, is also a reciprocal transducer, then the measurement of the fourth electrical transfer impedance can be used to determine the validity of the assumption of reciprocal behaviour.

2.4.2 Comparison

The calibration of hydrophones or projectors in free field conditions may also be accomplished by use of a reference acoustic transducer which has previously been subject to an absolute calibration. Such a calibration requires the use of either a calibrated hydrophone or a calibrated projector.

NOTE Calibration by a comparison method will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference device will inevitably introduce an extra Type B component of uncertainty.

The sound field generated by an auxiliary projector in water is measured at a point in the acoustic far field with a calibrated reference hydrophone. The reference hydrophone is then replaced by the hydrophone under test. The ratio of the open circuit voltages of the two hydrophones is equal to the ratio of their free field sensitivities, enabling the free-field receive sensitivity of the hydrophone under test to be determined. The auxiliary projector need not be calibrated, and needs to be stable only for the duration of the calibration **[1]**.

2.4.3 General considerations

Either calibration method can be chosen and completed in conformance with international standards **[5]** however there are also a number of key aspects to consider in order to get a calibration that has been conducted in both an arrangement (mounting configuration) and environment comparable to that which will be experienced in the field measurements. Below is a list of aspects for consideration when calibrating any hydrophone:

- It is advisable, prior to any calibration in water, to complete a process often referred to as ‘wetting’ of the hydrophone. This ensures that the surface of the hydrophone is free of grease and dirt, and prevent air bubbles from adhering to the surface and causing distortion of the measured signal.

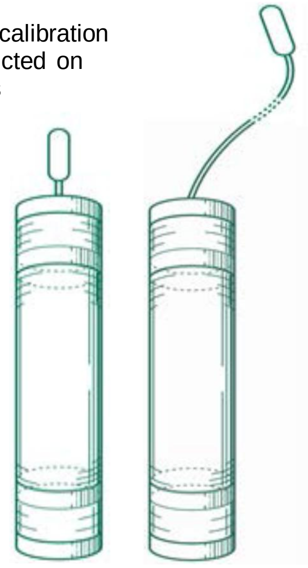
- Wherever possible, it is good practice to calibrate any hydrophone in the mounting arrangement that it will be deployed in. This is because some hydrophones, the response may show a dependence on the mounting used.

- During the measurements, if extra cable is added to the hydrophone (extra being a longer length of cable that has been used in the calibration) then it should be noted that this will reduce the overall sensitivity for hydrophones which do not have an integral preamplifier. For any hydrophones which do have a built in preamplifier, adding cable will not affect the sensitivity of these devices.

- Also, some hydrophones may show a varying response dependent on temperature or depth. If the conditions in the field measurement are significantly different from those in the calibration, then this can add uncertainty to the measurements. If there is evidence that the hydrophone performance varies significantly with temperature/depth, the calibration should be undertaken as close to the application conditions as possible. If this is not possible then corrections should be made using data for variations in performance with temperature/depth. Alternatively, a hydrophone should be chosen which has a stable performance with temperature/depth **[1]**.

2.5 Autonomous recorder calibrations

Currently there are no formal standards in place to provide guidance on the calibration of autonomous recorders, however a number of studies have been conducted on the area which can offer insight into the requirements for these calibrations and the challenges that are likely to be encountered **[14].**



Two configurations of autonomous recorders.

Figure 1 shows two configurations of autonomous recorders. The first one on the left has the hydrophone rigidly attached to the recorder body or with a short cable keeping the hydrophone in close proximity to the recorder body. This variation requires that the hydrophone be calibrated while attached to the recorder. This is to ensure that any effects on the recorded signal, due to the proximity of the hydrophone to the recorder body, can be identified as part of the calibration **[3, 21]**.

The second configuration for autonomous recorders that can be deployed, is also shown on the right in figure 1. This variation has the hydrophone attached by a length of cable. This deployment method can reduce the effects on the system sensitivity caused by the recorder body by separating the hydrophone and the recorder. The calibration required is still that of the whole recorder system (the combination of hydrophone(s) and electronic components), because the hydrophone is deployed remotely from the recorder, this offers the possibility of calibration of the hydrophone separately from the recorder body. In some respects, this simplifies the acoustic calibration because the influence of the recorder body on the performance is minimized. However, in this case the separate calibrations of the hydrophone and recorder must be combined to form the overall system sensitivity. In doing this, the overall system sensitivity may not just be the simple sum of the hydrophone and recorder sensitivities, and care must be taken to take account of any electrical loading effects **[3, 15].**

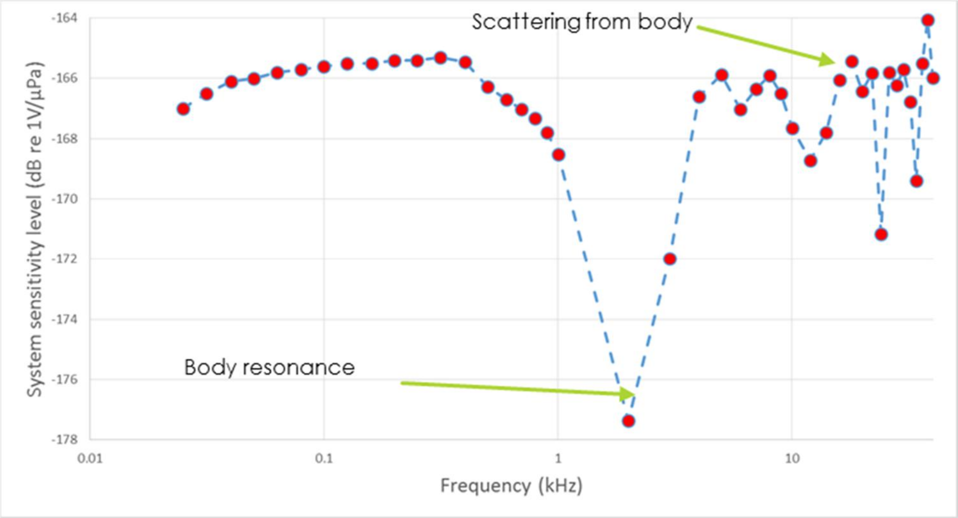


Figure 1. Example of the frequency response of a recorder with hydrophone fixed rigidly to the body.

Regardless of which variation is selected, the calibration itself should still conform to the international standard as far as possible. **[5, 6]**

2.6 Calibrations checks in-situ

It is advisable to undertake in-situ checks on the system calibration just before and after deployment, and in between any repeated deployments **[8]**. To do this, it is advisable to make use of a commercially available hydrophone-calibrator, which provides the hydrophone with a signal of known amplitude at a single-frequency (commonly at 250 Hz). The calibrator typically consists of an air-pistonphone that generates a known sound pressure level inside a small coupler into which the hydrophone is inserted. The sound pressure depends on the free-volume inside the coupler when the hydrophone is inserted, and so the coupler must be calibrated for each type of hydrophone that is used with it **[1]**.

Although the hydrophone calibrator provides a check at only one frequency, it does allow the entire system to be checked using an acoustic stimulus. It is also possible to undertake electrical check calibration of the system components. If the hydrophone in use has an insert voltage capability (many commercial hydrophones with integral preamplifiers have this facility), this may be used to check the electrical integrity and perform a calibration by electrical signal injection. This is a useful technique when deploying long cabled systems from vessels, and can be performed without retrieving the hydrophones. However, the method does not perform an acoustical check on the hydrophone element **[1, 7]**.

2.6.1 In-situ QA checks

It is good practice to, where possible, undertake Quality Assurance (QA) checks on the measured data before the deployment or sea-trial **[15]**. If a problem with corrupted data is discovered only after the return to shore base, it is usually too late to remedy the problem. However, early discovery of a problem may allow it to be solved during the deployment.

Good quality assurance checks include:

- Visual display of some measured data in real time during deployments provides confidence that data are present and are not exceeding the dynamic range of the system. This is possible for shore-based cabled systems; this is only possible for autonomous recorders if they are fitted with some telemetry (for example, using RF transmissions or wi-fi)
- Audio playback of data through speakers during the data acquisition process (for cabled systems) or after retrieval (for autonomous recorders) also provides a good check on data quality, and may indicate the presence of other clipping or artefacts due to deployment such as rubbing and abrasion of rigging and cables (only useful for signals in the human audio band but this is applicable to JOMPAN frequency range);
- When autonomous recorders are retrieved to replace batteries and extract recorded data, it is a good idea to read (and perhaps play back) recorded signals as a check on quality of data. If the equipment has failed or data are corrupted, there may be an opportunity to correct the problem before the next re-deployment or exchange the recorder for one that is functioning (depending on circumstance)
- Check for unexpected transient signals, for example from impacts on the hydrophone by rigging or moorings
- Check that the signal level and frequency content is within expected range
- Check that hydrophones deployed very close together show similar signal levels – for example two hydrophones deployed on the same mooring. The signals should not be identical, but closely positioned hydrophones with signal levels differing by many decibels may be indicative of a possible error
- It can sometimes be useful to deploy a local source (for example, a pinger) to provide a signal which all hydrophones receive. This can be used for calibration checks of the hydrophone and instrumentation if the source is calibrated and the source-receiver distance is known reasonably accurately. This is a good capability to introduce to a cabled system which is difficult and expensive to retrieve for repeated recalibration. In such cases, it is better for the source to be controlled from the shore base such that is can be switched on and off when required and does not generate interfering acoustic signals to the recordings.
- The measured recording should be checked for artefacts in the signals due to deployment issues (see Section 3 for more details). One example is flow noise generated in areas of high tidal flow – flow noise will tend to show strong temporal correlation with tides.

It is recommended that QA should be carried out on all measurement systems on retrieval and re-deployment.

2.7 Recommendations

- Calibrations should be completed on all devices before and after the deployments.
- Absolute calibration should be obtained for any measurement hydrophone and recording system deployed for the study.
- Calibrations should ideally be completed in the same (or as close as possible) mounting configuration and temperature/depth for which the hydrophone is likely to experience in the field.
- Field calibrations should also be conducted prior to deployment and post recovery to ensure there has been no major change in the hydrophones response over the course of the measurement.
- Recommended frequency range for calibrations should at minimum cover the frequencies of interest between 10 Hz and 20 kHz at least third octave centre frequencies.
- All calibrations must be traceable to internationally-recognised standards

3 Specification of deployment methodology

3.1 Background

3.1.1 Types of deployment

For JOMOPANS, this is either bottom-mounted archival recorders, or bottom-mounted systems that are hard-cabled to shore

3.1.2 Examples of deployment

Static systems are more appropriate for longer-term deployments. Typically these can be used for monitoring using either continuous recordings, or time-sampling with a specific duty cycle for periods of weeks or months. This enables the measured data to be sampled over a range of variable conditions such as tidal cycles, weather conditions and operational states for example.

A bottom-mounted deployment is preferable to a surface deployment to minimise parasitic signals from the influence of surface wave action. This is to keep the hydrophone away from the pressure-release water-air surface, and to minimise disturbance by surface vessels to recordings **[1, 2]**.

Bottom-mounted autonomous recorders

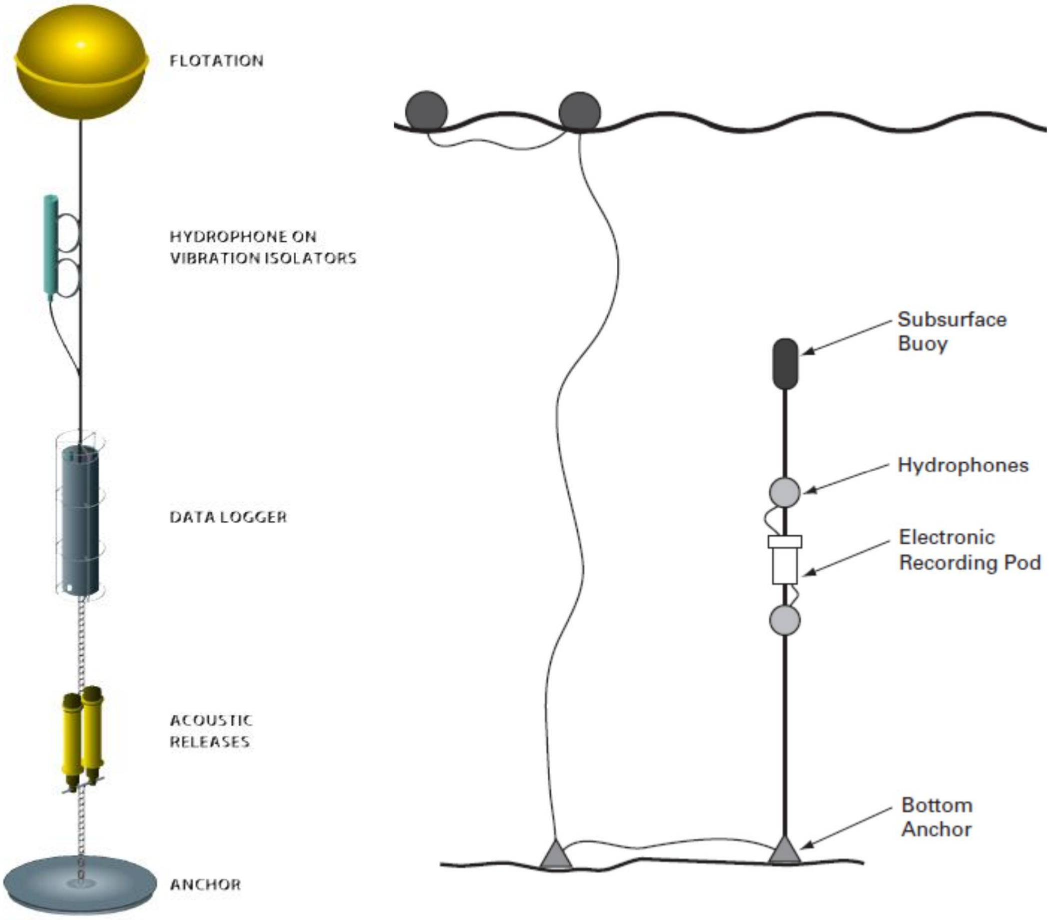


Figure 2. Examples of the bottom-mounted autonomous recorder deployment configurations.

Bottom mounted autonomous recorders provide the opportunity to deploy a hydrophone anywhere in the ocean with the data being stored with the unit and thus, no requirement for a length of cable. Figure 2 shows examples of the bottom mounted autonomous recorder deployment method. From this figure we can see that the system is attached to an anchor to take the recorder down to the bottom, and then a subsurface float to lift the hydrophone/recorder to the required depth.

There is a requirement for an acoustic release mechanism to be fitted between the recorder and the anchor on the left option, this is for retrieval purposes so when activated the recorder can be separated from the anchor and the float will bring it to the surface ready for collection. The option on the right is for deployment and retrieval of a system where acoustic release is not available. Surface floats are necessary with additional anchor to de-couple potential drag by the surface floats to the recording system. The system can be recovered easily with the surface floats. The disadvantage of this configuration is that there is a risk the system can be intentionally or un-intentionally picked up or moved by the surface floats.

As stated in section 2.5, there are two configurations of autonomous recorder. Figure 2 shows the system with an extension cable separating the hydrophone from the body of the recorder/data logger. NOTE: This is the recommended deployment method for anyone using the autonomous recorders.

Bottom-mounted systems hard-cabled to shore

Bottom mounted systems (sometimes referred to as a ‘static system’) have a hard wired cable running to a shore base which is the other deployment option in this project. A bottom-mounted deployment is preferable to a surface deployment as it helps to minimise parasitic signals from the influence of surface wave action, to keep the hydrophone away from the pressure-release water-air surface, and to minimise disturbance by surface vessels **[1]**. A deployment setup of this type has the advantage of near real-time data availability and enables checks of system functionality to be performed **[16].** However, such configurations are expensive and not readily available commercially. This deployment method also has the limitation that the length of cable dictates the potential deployment locations.

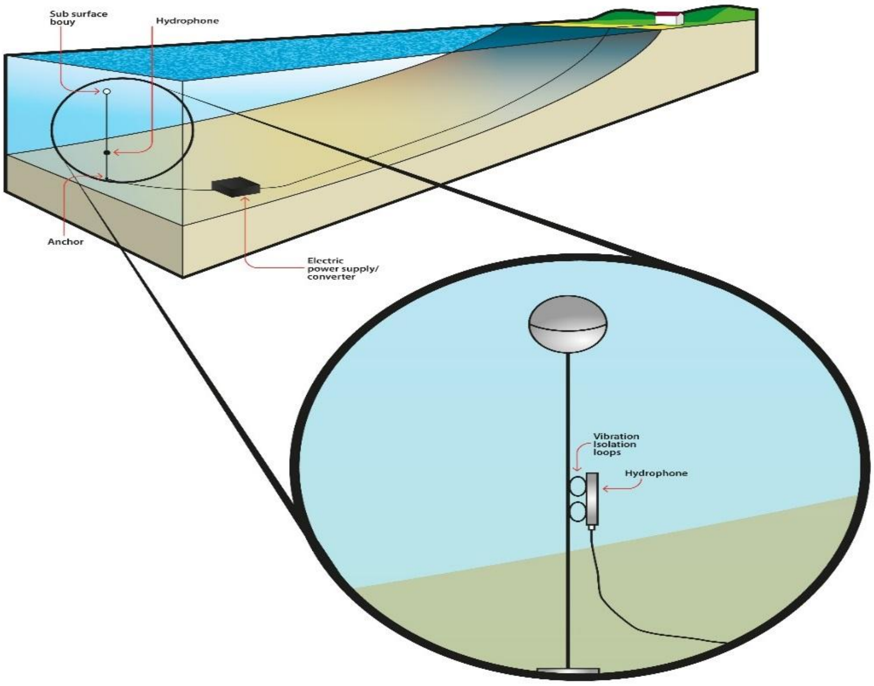


Figure 3. The Bottom-mounted hard-cabled to shore deployment option.

Figure 3 is showing a diagram of the bottom mounted ‘cabled to shore’ deployment method. The deployed hydrophone is weighed down by an anchor which is connected to a sub-surface buoy via a riser cable. The hydrophone should be connected to the riser cable using some form of vibration isolation. This will dampen the effects of vibrations travelling through the cable (to the hydrophone) which are the result of flow movement within the medium. When deploying via this method, the hydrophone should be positioned in the lower half of the water column ensuring an adequate distance between the subsurface buoy and the electronics to avoid interference.

Considerations when deploying via the cabled to shore method

The hydrophone should be positioned within the lower half of the water column, ensuring an adequate distance separating the hydrophone, any electronics housing and the sub-surface float. The hydrophone should also be attached to the riser cable with vibration isolators to reduce any vibrations the hydrophone feels as a result of the movement of the cable within the water column.

Due to the length of the trunk cable required for most ‘cabled to shore’ deployments, it is often that the electronics housing with an electrical power supply be located relatively close to the device to provide power to the pre-amplifier of the hydrophone and possible other electronic devices. The presence of this power supply can cause interference if the hydrophone is mounted to close and so this should be taken into account when deploying these systems.

As there will also be a cable in close proximity to the hydrophone, there is a potential for parasitic signals to be produced. The possible sources of noise to consider include;

- Flow noise
- Cable strum
- Mechanical noise

See section 3.2 for more information about these sources of parasitic signals and methods for mitigation.

3.2 Sources and mitigation of parasitic signals

In addition to the self-noise of the measuring system itself, the measured data may also be contaminated by signals originating from the platform or method of deployment. This is often called “platform noise” or “deployment noise”. These parasitic signals are due to the deployment method for the hydrophone and recording system and its interaction with the surrounding environment (e.g. current, wave action, etc.) **[1]**.

3.2.1 Flow noise

Any flow of the medium relative to the hydrophone or cable can induce turbulent pressure fluctuations at low frequencies that will be sensed by a pressure sensitive hydrophone. This noise is produced in a turbulent layer around the hydrophone, and is analogous to wind noise on a microphone. It is not a true acoustic signal (it does not arise because of a propagating sound wave from a source remote from the sensor) and its existence depends upon the presence of the hydrophone (and its support structure) in the flowing water. It gives rise to low frequency signals (typically <100 Hz), with the frequency being dependent upon the hydrophone diameter and the speed of the current **[17, 18]**. It can be the major source of deployment noise in high flow environments, for example in strong tidal currents. For autonomous recorders where the hydrophone is protruding from the recorder body, the problem can be exacerbated by turbulent flow around the end of the recorder casing or hydrophone guard. Strong fluid flow can also cause vibration of moorings and excite resonances in the recorder body.

It is not always easy to check for the presence of flow-induced noise, but for long-term deployments, the recorded signals at low frequencies (<100 Hz) should be checked for correlations with tidal information – the flow noise signal will often show the same cyclic variations as the tidal current. If measurements have been made at both slack tide and at full tidal flow, it may be possible to quantify the effect of flow noise by comparison of the data sets **[1]**.

Mitigation: A classic method of reducing flow noise is by use of an acoustically-transparent sonar-dome (analogous to a microphone windshield), which moves the turbulent fluid layer away from the hydrophone’s sensing element. However, this may not always be a practical solution. Alternatives include locating the hydrophone close to the seabed where the current flow is reduced, or measuring at slack tide where the tidal current is minimised.

The other main mitigation is to employ *drifting systems* where the system moves with the current and the relative motion of the hydrophone and medium is essentially zero **[19].** These have some disadvantages as a deployment configuration, but they are probably the preferred option for regions of very high current (for example, at the locations of tidal stream energy developments).

3.2.2 Cable strum

Cable strum occurs when cables are pulled taut by the action of currents, and the cable is then caused to vibrate by the action of the water flow around it, producing parasitic low frequency signals. The effect is similar to the “Aeolian harp” effect, or the singing of telephone wires in the wind. For typical cable diameters and currents, signal frequencies are of the order of 10 Hz (1 cm diameter cable in a current of 1 knot produces a signal of frequency 9 Hz) **[8]**. Even if the hydrophone is mounted on a rigid pole, severe current can induce the pole to “flap” and cause parasitic vibration.

Mitigation: The effect can be mitigated by use of bottom-mounted deployments, and by the use of mechanical fairings, often in spiral or helical form around cables and housings **[17, 18, 20]**. However, bottom deployed hydrophones on long riser cables may be subject to significant displacement and strum due to tidal flow. If surface deployments are used, decoupling of the hydrophone from suspension cables using compliant couplings (for example, using elastic rope) will reduce the problem **[1]**.

3.2.3 Mechanical noise

Sources of mechanical noise includes:

- Debris and/or sediment impacting the hydrophone
- Biological abrasion noise
- Hydrophone and cables rubbing against each other
- Mooring cables rubbing together.

Any opportunity for parts of the mooring system to impact against each other will cause noise, which may be picked up by the hydrophone. This is especially true if the mooring involves metal parts which can come into contact (for example, chains) **[15, 17].**

Mitigation: To minimize the problems: avoid using metal moorings if possible; avoid metal coming into contact with metal (such as with shackles); avoid the use of chains in the moorings and supports; avoid placing hydrophone so close to the seabed that sediment can impact on the hydrophone; avoid hydrophones touching the support cables by attaching them with vibration isolators (compliant couplings) **[1]**.

3.2.4 Electrical noise

Electrical noise can also be a significant source of parasitic signals. For vessel-based deployments, preferably the generator should be switched off (as well as the engine) to avoid electrical interference (electrical supplies on vessels can suffer from electrical noise). The instrumentation must then be powered by batteries.

Severe electrical pick-up can sometimes arise from “ground loop” effects; again this is more problematic when the instruments are deployed from a vessel. The hydrophones and acquisition system should have proper electrical shielding to minimise the problem. To ascertain whether the hydrophone is susceptible to electrical pick-up, a simple “bucket test” may be performed where the device is immersed in a bucket of sea-water and electrical signals can be induced via a wire in the bucket which is driven with an oscillating electrical signal.

Mitigation: If ground loop pick-up is a severe problem, consider reverse coiling the cables on deck, or even keeping excess cable in a bucket of sea water.

3.2.5 Biofouling

It should also be noted that long-term deployments may need servicing at intervals to remove biological fouling **[1, 2]**.

3.3 Protection from damage or loss

When choosing a final deployment location it is important to know the risk of damage or loss of equipment (and data) after deployment has been completed. This is a problem commonly encountered with long term deployments using autonomous systems. Mainly from extreme weather and fishing activity.

Care and consideration should be taken when designing the system to endure severe weather. An appropriate weight and anchor should be used to mitigate the chance of the system relocating its anchoring position. Also any attempts in streamlining the shape of the equipment should avoid accidently creating an aerofoil effect with its design, as during high flow currents can lift the system off the seafloor.

Particular care should be taken in the decision of the deployment location to avoid damage from fishing. Some bottom-mounted designs have used an enclosed, cage-like form to protect against the system being caught and retrieved by fishing nets. However, in such cases, there may still be damage to hydrophones and cables, even though trawling is normally done at low speeds (less than 5 knots). It is advised to avoid fishing areas if possible. Ideally the location can be adjusted to an area with lower fishing frequency, thereby minimizing the probability of loss or damage. An additional note is deployment locations near ship wrecks can prove beneficial, as these areas are often avoided by fisherman, which would also minimize the risk of damage or loss.

Before deployments all relevant local authorities and stake holders should be informed of operations in deployment areas. These would include fishing industry, shipping and navigation. It could be advantageous to increase awareness by publicising the deployment in the local community via notices to mariners and the Kingfisher bulletin. All equipment should be labelled so that if accidentally retrieved or found, it may be returned.

In addition to loss of equipment, there is also a risk of loss of data. For long-term deployments, this can have a significant cost. If there is communication with the recording system via telemetry or a cabled system, some data may be retrieved continually during the deployment. However, for autonomous recorders with archival storage, the data is only available periodically after recovery. In such cases, the use of shorter intervals between data recovery will mitigate against data loss (though deployment costs will be increased) **[1].**

3.4 Recommended deployment options

The recommended deployment option will be split into two separate recommendations due to the intended use of both autonomous recorders and cabled systems. They are listed below;

3.4.1 Bottom-mounted recorders

Bottom mounted recorders are rigs that can hold a variety on instruments that save all data on to on-board recorders. These recorders are then retrieved later at pre-set, time intervals to collect the data so that it can be analysed. This means data is not always readily available but can record data over set time periods of long durations (weeks or months). This is a cheaper system compared to a cabled back to shore system, and equipment can be relocated to different locations with relative ease **[1]**.

The design of the instrumentation rigging should be in such a way as was described in section 3.1.2 so not to generate aerofoil effects and to have an adequate anchor / weight to hold the rigging in position.

Environmental systems attached to the instrument set up should be calibrated before and after deployments following manufacturer’s instructions. Sensors mounted should be in a position where they have access to flowing seawater and do not interfere with other sampling instruments also mounted **[1-4]**.

3.4.2 Systems cabled back to shore

These systems are similar to the bottom mounted recorders, but are positioned in fixed locations, can remain in a fixed location for longer periods of time than bottom-mounted recorders and are connected to a nearby shore base supplying power, which can receive the data almost instantaneously. This is achieved by either cable, and may be communicated further through satellite or a internet link.

This gives the advantage of instant retrievable data and protects against data loss of long duration recordings, but such configurations are expensive and not readily available commercially.

3.5 Recovery of measurement systems

It is most likely that only the autonomous recorder systems are to be recovered from deployment, either for data retrieval and then re-deployment or on completion of measurements. It is straight forward to recover a system fitted with acoustic release by activating the device to allow the subsurface float to surface ready for being picked up. It is also easy to recover the systems without the acoustic release from their surface floats. See section **3.1.2** for more information on the systems that will be recovered.

It will be useful to inspect the system for any damage at the time of the recovery, and to perform in situ calibration check as recommended in Section **2.7**.

The cabled to shore systems are most likely going to remain at their deployment location and so recovery of these systems will not be described here.

3.6 Auxiliary and meta-data

Auxiliary and meta-data refers to any data recorded that is surplus to the measurement data. This data that may be relevant, since it can be used to correlated with the measured noise levels during analysis and so it is always beneficial to record. This is of general importance, but is particularly useful when measuring ambient noise data. This will enable an investigation of the dependencies of the measured data on other environmental factors such as weather. Some of the information may be obtained from other sources (for example, wind speed data), but if measured locally, this may require the deployment of auxiliary equipment. Depending on the availability this may or may not be possible, and any deployment of auxiliary equipment must not generate any additional noise **[1]**.

Relevant auxiliary data to record may include (if available):

- Sea-state
- Wind speed (and associated measurement height)
- Rate of rainfall and other precipitation, including snow
- Water depth and tidal variations in water depth
- Water temperature (and air temperature)
- Hydrophone depth in the water column
- GPS locations of hydrophones and recording systems
- Seabed type
- Profile of conductivity, temperature and hydrostatic pressure as a function of depth using a CTD probe (or sound speed with velocimeter) recorded during deployment
- Vessels in the area (by means of AIS/VMS data)
- The presence of any distant noise generating activity such as geophysical surveying
- Nearby ship wrecks
- Nearby military restricted area
- Nearest marine reserve
- Permanent anthropogenic sound sources (windfarm, oil and gas platform) **[1-4]**

3.7 Data Storage

To avoid degradation of the data quality, the data format used to store the data should ideally be lossless (no data compression). If data compression formats are used in order to increase the storage capacity (and thereby the recording duration), the effect on the data quality should be known.
Any crucial auxiliary data or metadata that are needed for interpretation of the results should be recorded (for example, the scale factor or setting of the ADC, or the gains of any amplifiers, the sampling frequency and the resolution).

It is desirable that such calibration data information be included in a file header or log file so that the information is kept with the data. Without this information, the data file may essentially be “uncalibrated”. Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data **[8]**.

If data storage is required to be long-term (many years), consideration should be given to the likely future compatibility of the storage media and data format. Note that some formats and storage media may become obsolete over time **[1]**.

References

1. *Good Practice Guide for Underwater Noise Measurement*, National Measurement Office, Marine Scotland, The Crown Estate, Robinson, S.P., Lepper, P. A. and Hazelwood, R.A., NPL Good Practice Guide No. 133, ISSN: 1368-6550, 2014.

2. *BIAS Standard* for *Noise Measurements, Background information and Guidelines* https://biasproject.files.wordpress.com/2016/04/bias_standards_v5_final.pdf

3. UNAC-LOW Underwater Acoustic Calibration Standards for Frequencies Below 1kHz (https://www.euramet.org/research-innovation/search-research-projects/details/?eurametCtcp_project_show[project]=1406)

4. Atlantic Deepwater Ecosystem Observatory Network (ADEON): An Integrated System for Long-Term Monitoring of Ecological and Human Factors on the Outer Continental Shelf **(https://adeon.unh.edu/standards)**

5. EN 60565: 2006 or BS 60565:2007, Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz, International Electrotechnical Commission, Geneva, Switzerland, 2006.

6. IEC 61260-1:2014 or BS EN 61260-1:2014, Electroacoustics — Octave-band and fractional-octave-band filters, International Electrotechnical Commission, Geneva, Switzerland, 2014.

7. BS ISO 18406:2017, Underwater Acoustics – Measurement of Radiated Underwater Sound from Precussive Pile Driving, ISO (the International Organization for Standardization), Switzerland, 2017.

8. [EU TSG Noise 2014b] “Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications”, Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the, European Union, Luxembourg, 2014, doi: 10.2788/27158, ISBN 978-92-79-36339-9. Available from: **(http://publications.jrc.ec.europa.eu/repository/handle/111111111/30973)**

9. IEC 60500:2017, Underwater acoustics – Hydrophones – Properties of hydrophones in the frequency range 1 Hz to 500 kHz, International Electrotechnical Commission, Geneva, Switzerland, 2017.

10. Lammers M.O., Brainard R.E., Au W.W.L., Mooney T.A., Wong K., "An Ecological Acoustic Recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats"., J. Acoust. Soc. Am., vol. 123, 1720-172, 2008.

11. ANSI/ASA S1.20-2012, Procedures for Calibration of Underwater Electroacoustic Transducers, American National Standard Institute, USA, 2012

12. Wenz, G. M., "Acoustic ambient noise in the ocean: Spectra and sources," ., *J. Acoust. Soc. Am.* vol. 34, p. 1936–1956, 1962

13. Knudsen V.O., Alford R.S., Emling J.W., "Underwater ambient noise", Journal of Marine Research 7: 410-429, 1948

14. G. Hayman, S. P. Robinson, T. Pangerc, J. Ablitt and P. D. Theobald, "Calibration of marine autonomous acoustic recorders," OCEANS 2017 - Aberdeen, Aberdeen, 2017, pp. 1-8. doi: 10.1109/OCEANSE.2017.8084773

15. Harland E J., "Measuring underwater noise: Perils and pitfalls" Proceedings of the Institute of Acoustics vol. 30. Pt.5,2008

16. André, M., van der Schaar, M., Zaugg, S., Houégnigan, L., Sánchez, A., and Castell, J. V., "Listening to the deep: Live monitoring of ocean noise and cetacean acoustic signals", Marine Pollution Bulletin, vol. 63, 2011, pp. 18-26.

17. Cato D.H., Ocean ambient noise: its measurement and its significance to marine animals., Proceedings of the Institute of Acoustics, vol. 30. Pt. 5, 2008.

18. Ross, D., *Mechanics of Underwater Noise,* Peninsula Publishing, Los Altos, CA, 1987.

19. Wilson B., Lepper P. A., Carter C., Robinson S. P., "Rethinking underwater sound recording methods to work in tidal-stream and wave energy sites"., In Marine Renewable Energy and Environmental Interactions, Humanity and the Sea, M. A. Shields, A. I. L. Payne (eds.), DOI 10.1007/978-94-017-8002-5_9, © Springer Science+Business Media, Dordrecht, 2014

20. Urick, R., *Principles of Underwater Sound for Engineers*., New York: McGraw-Hill, 1984.

21. Alper Biber, Ata Can Çorakçı, Alexander Golick, Stephen Robinson, Gary Hayman, Justin Ablitt, Salvador Barrera-Figueroa, Silvano Buogo, Salvatore Mauro, Fabrizio Borsani, Salvatore Curcuruto, Markus Linné, Peter Sigray, Per Davidsson. "Calibration standards for hydrophones and autonomous underwater recorders for frequencies below 1 kHz: current activities of "UNAC-LOW" project", *ACTA IMEKO*, June 2018, Volume 7, Number 2, 32-38, 2018.