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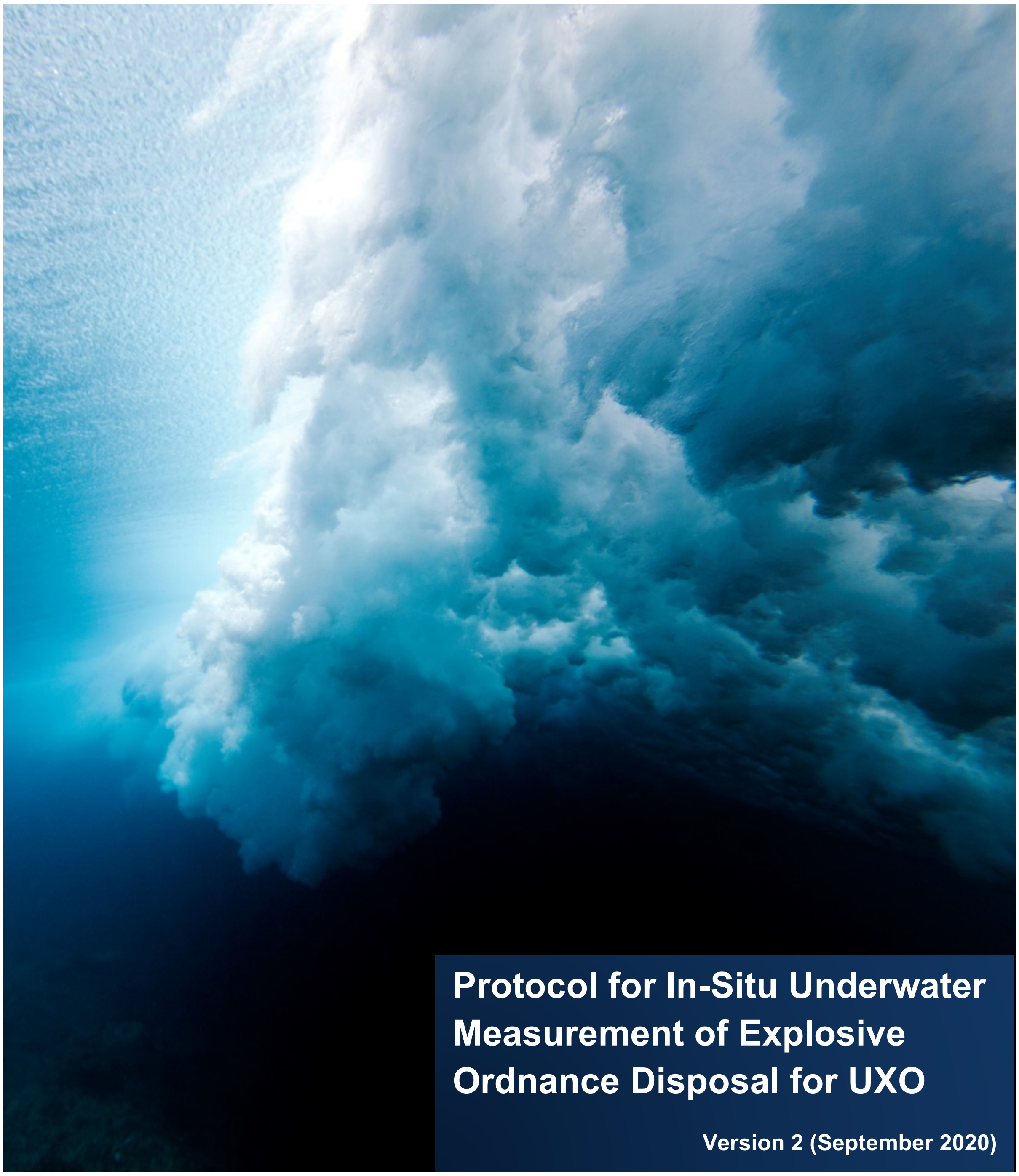

Protocol for In-Situ Underwater Measurement of Explosive Ordnance Disposal for UXO

Version 2 (September 2020)

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Summary

This document provides guidance on best practice for *in-situ* measurement of underwater sound generated from underwater explosions undertaken during disposal of unexploded ordnance in the ocean. In recent years there has been an increasing need to measure and report levels of underwater sound generated by these explosions, partly driven by the need to conform to regulatory requirements with regard to assessment of the environmental impact. Attempts to report measured noise levels are sometimes difficult to compare if different methodologies and acoustic metrics are used. This good practice guide aims to provide guidance on best practice for measurement and for reporting the results using common methodology.

The work to prepare this document was funded in the UK by the Department for Business, Energy and Industrial Strategy through its Offshore Strategic Environmental Assessment programme.

Version 2
September 2020

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This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the through its Offshore Energy Strategic Environmental Assessment programme.

Contents

Glossary

Abbreviation	Terms
ADC	Analogue to digital converter
BEIS	Department for Business, Energy and Industrial Strategy, UK
DAC	Digital to analogue converter
dB	Decibel, a logarithmic unit expressing the ratio of a quantity relative to a reference value
EOD	Explosive ordnance disposal
Hz	Hertz, unit of frequency
JNCC	Joint Nature Conservation Committee
NMFS	National Marine Fisheries Service, USA
NOAA	National Oceanic and Atmospheric Admiration, USA
PTS	Permanent Threshold Shift
SEL	Sound exposure level
SPL	Sound pressure level
TTS	Temporal Threshold Shift
UXO	Unexploded ordnance

1. **Introduction**

1.1 Background

Unexploded Ordnance (hereafter UXO) in the marine environment constitutes a major environmental and safety issue. The UXO contamination typically originates from World War I & II bombing and shelling, defence mining, munitions dumping, coastal defences and anti-submarine weaponry. These munitions are slowly degrading in the ocean, and there is a risk of spontaneous detonation.

This presents significant risk to offshore development projects where developers are building infrastructure directly on the seabed, such as offshore windfarms or oil and gas platforms. As part of marine licensing, developers are required to identify these munitions and dispose of them. Removal of large UXOs are often difficult and disposal is typically undertaken through the use of detonation of the munition. This in turn generates very high amplitude underwater sound which poses significant risk to the marine wildlife within close proximity of the exercise.

Underwater explosions can produce some of the highest sound pressures of all anthropogenic sound sources with the potential to cause fatality and auditory damage to animals in the marine population. The current mitigation measures are based on the JNCC guidelines [JNCC 2010], and recently revised exposure criteria [e.g. NMFS 2018, Southall et al. 2019] are typically applied to establish the impact distance at which detonations could cause physical injury as part of the noise risk assessment. However, estimates of the injury zone can exceed the practical mitigation prescribed in the mitigation protocol, which raises concern about the effectiveness of current practice.

In general, underwater explosions create shock waves (sometimes termed “blast waves”) in the vicinity. These are high-amplitude waves where there is a very fast initial rise time, and whose propagation is governed by the nonlinear wave equation. However, at the distant measurement locations where monitoring is typically undertaken, the waves are typically propagating linearly [Cheong et al 2020].

1.2 Background

This document describes the recommended methodologies, procedures and measurement system to be used for the measurement of the radiated underwater sound generated during detonation of UXO. The motivation for undertaking measurement of the sound radiated by the explosion is the requirement for assessment of impact on aquatic fauna by regulatory frameworks for offshore development. Collection of data in a common manner also facilitates the filling of current data and knowledge gaps on direct measurements of underwater noise generated by explosions on the seabed.

This document aims to provide a generic approach to measurements that can be applied to regulatory requirements, whilst providing a common approach to help offshore operators and developers to collect underwater acoustic measurement in order to help the further understanding of the impact of explosive sounds in the ocean.

This document is suitable for measurement of underwater sound generated during an Explosive Ordnance Disposal (EOD) operation, commonly undertaken in construction of offshore windfarms, oil and gas platforms, and construction of other marine renewable energy devices (MREDs). The EOD may be undertaken by either high order detonation (where a substantial donor charge is used to detonate and destroy the UXO), or low order detonation where a smaller charge is used to disrupt and/or consume the UXO. An example of low-order detonation is deflagration [Robinson et al 2020]. This document covers only the measurement of the radiated sound field in shallow water (<100m).

The guidance in this document covers:

- choice of hydrophone and acquisition systems, including calibration requirements;
- deployment techniques;
- minimum requirement for measuring radiated noise from UXO;
- data handling and storage;
- reporting requirement.

The beneficiaries of this work include consultants, offshore developers of marine renewable energy; regulators wishing to base their requirements on a common scientific foundation; and in general, all those making *in-situ* acoustic measurements of underwater explosions. The guidance contained herein facilitates comparison between measurements of radiated noise from high order detonation as well as low order detonation from underwater explosion.

2. Instrumentation

2.1 General

This section describes the requirement for the measuring instrumentation and specifies the key performance specifications, system calibration and other data quality measures. The document provides no recommendation of instrumentation choice to a specific manufacturer or equipment type. It only aims to provide minimum specifications to the measuring instrumentation to militate against any bias caused by equipment choice and measurement methods, and ensure consistent information is collected for all future UXO detonation.

The measuring system generally consists of the following instruments:

- Hydrophone(s)
- Signal conditioning equipment (such as amplifier(s) and filters)
- Signal digitization and data acquisition equipment
- Data storage

The measuring system may consist of individual components as listed above or as an integrated system such as an autonomous recorder that provides a self-contained recording system powered by batteries. The amplifier can also be a separate element in the system to allow an adjustable gain, or it can be an integral part of the hydrophone but without flexibility of a gain adjustment [BS ISO 18406: 2017].

2.1.1 Hydrophones

Hydrophones are devices that detect changes in pressure in water. A hydrophone converts these pressure changes into an electrical voltage signal, which will then be passed on to other components of the system. Hydrophones used should be calibrated in conformance with a specification standard describing standardised procedures such as IEC 60565-1:2020, IEC 60565-2: 2019 or ANSI/ASA S1.20:2012. As far as possible, hydrophone sensitivity should be invariant at the frequency of interest. The sensitivity is typically expressed in units of V/Pa, or as a sensitivity level in decibels as dB re 1 V/µPa, at a succession of discrete frequencies, or in the form of a calibration curve [BIAS, NPL 2014].

Note that if extra cable is added to a hydrophone, this reduces the overall sensitivity for hydrophones without an integral pre-amplifier, however this will not affect the sensitivity of hydrophones with built in pre-amplifiers. The reduction of sensitivity of the extension cable must be characterised to correct the data before analysis, such guidance is detailed in [IEC 60565-1:2020].

2.1.2 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 voltage amplitude gain (e.g. “times 10” or “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. [NPL 2014]

2.1.3 Filters

A filter defines a range of frequencies of a signal which can pass through to the rest of the system, rejecting frequencies outside of this range. Filters are typically known as low pass, high pass or bandpass depending on their frequency response. Filters serve a number of purposes: (i) to reduce the influence of very low frequency parasitic signals (a high pass filter designed to cut out frequencies of less than 10 Hz which can be generated by non-acoustic mechanisms such as surface motion and flow noise – such filters are commonly incorporated into commercial hydrophones which have integral preamplifiers); (ii) to provide some signal equalisation across the frequency range (usually, this involves a high pass filter with a modest slope which is designed to compensate for the frequency roll-off observed in typical ambient noise spectra, thus avoiding saturation of the ADC). (iii) to provide an anti-aliasing function (a low pass filter designed to restrict the frequency content of the signal before digitization to below the Nyquist frequency of the acquisition system); If any of the above filters are used in the system, their performance needs to be known to correct the data before analysis [ISO 18406: 2017].

The filter performance is typically expressed as an insertion loss factor, a positive number expressed either as a linear factor or in decibels [IEC/BS 61260-1:2014]. By definition, a filter response varies with frequency, and must be characterised over the full operating frequency range of the system. Note that some commercial hydrophones with integral preamplifiers are designed with a high pass filter to remove frequencies less than about 10 Hz to minimize influence of very low frequency parasitic signals typically generated by surface wave motion and flow noise.

2.1.4 Analogue to Digital Converter (ADC)

An ADC is used to convert an analogue signal into a digital format to be processed / read by other components of the system analysing the signal. To characterise the ADC performance, the range setting (full-scale) and the calibration factor of the ADC must be known. This is often expressed as a digital sensitivity, 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. Alternatively, it can be expressed as a scaling factor, which is more commonly done when the ADC output file is formatted into a WAV file where the data is scaled between values of +1 and -1. In this case, the scaling factor represents the number to multiply the data by to obtain the sound pressure in pascals (and for a scaling to between +/-1, it represents the maximum sound pressure detectable by the system) [BIAS, NPL 2014].

2.1.5 Data storage

Once data is digitized it is saved in the form of digital files for storage. These files are typically transferred to an electronic storage media such as a computer hard drive or direct to flash memory which can read directly for post processing.

To avoid degradation of the data quality, data should ideally be recorded in lossless format to ensure analysis result is representative of the true sound level. If data compression is used (in order to increase storage capacity and recording duration), the compression technique must be reported, and compressed data should be recoverable to the uncompressed state to ensure data quality. All analysis should be carried out on uncompressed data.

In addition, any crucial metadata such as scaling factor, amplifier gains, sampling frequency must also be reported to aid the interpretation of results. For example, the scaling factor or range setting of the ADC, or the gains of any amplifiers, the sampling frequency and the resolution [NPL 2014].

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 appear "uncalibrated". Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data [NPL 2014].

2.2 Key performance of the measuring system

The following outlines the key characteristics for the measuring instrumentation and recommended setting with regards to measurement of underwater explosion.

2.2.1 Sensitivity

The sensitivity of the measuring system must be chosen to be an appropriate value for the amplitude of the sound signal being measured. The system should be specifically chosen to avoid nonlinearity and system saturation for high amplitude signals. Sound generated by explosion is of high amplitude when close to the source (with typical peak sound level exceeding 200 dB re 1 µPa within the first 500 meters), and system saturation can occur when the pressure amplitude exceeds its dynamic range. Thus, for measurements made close to the source, a relatively low sensitivity hydrophone and system is recommended (less than -200 re 1V/ µPa for use at a minimum range of 1 km). However, it should be noted that gain settings for many autonomous recorders and hydrophones with built-in preamplifiers cannot be modified after deployment, thus considerations must be given to its deployment position in order to avoid unusable data (a high-gain system may only be suitable for measurement at substantial distance from the source).

It is good practice that the background noise be reported with the results, preferable measured at the same location of the low sensitivity hydrophone. Note that it is not appropriate to use the low sensitivity hydrophone and system to take these background noise measurements with good accuracy. For background noise measurement, a low noise performance and high sensitivity is generally required to ensure good signal to noise ratio. The recommended system sensitivity level for background noise measurement is -185 to -165 dB re 1 V/µPa.

For *digital* systems, the system records the sound as a digital waveform (rather than providing an analogue voltage output). The calibration of the digitiser (analogue to digital converter) is incorporated into the overall sensitivity of the whole system including the digitizer. This may be termed the *digital system sensitivity*, which is the number of digital counts per unit change in sound pressure (unit Pa^{-1}). Sometimes, the digital system sensitivity may be represented as a scaling factor by which the digital waveform values must be multiplied by to obtain pressure values in pascals (this is equivalent to the *reciprocal* of the digital system sensitivity).

Note: In general, the measuring system may introduce a phase delay into the measured signal. This may be accounted for by representing the system sensitivity as a complex valued quantity, the modulus of which represents the magnitude-only response (and is described by the definition above), and the phase of which describes the phase response of the system.

2.2.2 Sampling Frequency and range

The frequency response of the measuring system shall be set to a frequency range sufficient to cover all frequency components of interest within the measured signals [IEC 60500:2017]. This requirement applies to the hydrophone or the measuring sensors, data acquisition system and amplifiers.

For the measurement of underwater explosions, **at minimum** the system nominal frequency bandwidth shall cover between 20 Hz – 20 kHz, with a minimum sampling frequency of at least 43.8 kHz (to capture upper band limit of 22.39 kHz for the 20 kHz third-octave band). However, when selecting a suitable frequency range for the measurements, consideration of the hearing abilities of the relevant receptors should be given on a case by case basis. Where the hearing response of relevant marine receptors extends to higher frequencies, the highest frequency of measurement should ideally be extended so that the sampling frequency is more than twice the value of the frequency of interest (or higher than the upper bounds of the highest one-third octave band) [ISO 18406:2017, NMFS 2018, Southall et al, 2019]. For example, to capture the typical audible range of harbour porpoise which extends to 150 kHz, a sample rate of the recording system should be selected at or above 300 kHz, at twice the frequency of interest.

It is desirable that the system sensitivity be invariant with frequency over the frequency range of interest to within a tolerance of 2 dB. The measuring system should be calibrated to a traceable standard as this will allow correction of the variation in the sensitivity of the instrument. [IEC 60565-1:2020, IEC 60565-2:2019, IEC 60500:2017]

2.2.3 Directivity

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

Omnidirectionality is generally easily achievable below 20 kHz due the small hydrophone size compared to the acoustic wavelength. However, if the hydrophone is placed close to a physical structure, the scattered sound may interfere with the direct sound wave and cause enhanced directionality at high frequency [ISO 18406 2017, Hayman *et al* 2017, NPL 2014].

2.2.4 Signal to noise ratio

Signal to noise ratio is defined as the ratio of the mean squared signal voltage to the mean square broadband noise voltage. A signal-to-noise ratio of at least 6 dB level difference shall be required for all measurements (including any background noise measurement).

2.2.5 System self-noise

System self-noise is considered to be the noise originating from the hydrophone and recording system and it is generated in the absence of any signal due to external acoustic stimulus. In order to achieve acceptable signal to noise ratio, the system self-noise shall be at least 6 dB below the lowest signal level in the frequency band of interest.

2.2.6 Dynamic range

The dynamic range refers to the measuring system's effective amplitude range over which the system can faithfully measure the sound pressure. This ranges from the lowest measurable signal (system self-noise) to the highest amplitude of a signal without distortion. This can be expressed in decibels representing the difference between the lowest and highest amplitude level of signal.

Sound generated by explosions has high amplitude and can often exceed the dynamic range of the measuring system and render the measured signal with "truncated peak", an effect known as clipping. In order to avoid clipping, consideration must be given to the dynamic range of the digitizer ADC and the analogue input of the hydrophone. The system dynamic range shall be chosen to be sufficient to enable the highest expected sound pressure, at the measurement position, to be recorded faithfully without distortion or saturation caused by the hydrophone, amplifier, and ADC. The measuring system is required to be linear over the full dynamic range, requiring that the system sensitivity is constant over the full range of measurable sound pressure. Systems with dynamic ranges of in excess of 60 dB are preferred for measurement of sound from explosions at ranges of a few kilometres.

As a minimum data shall be recorded in resolution no less than 16 bit in the analogue to digital conversion stage, with a nominal given system dynamic range of 96 dB. However, a 24 bit system with dynamic range of 144 dB is desirable for this type of measurement. The analogue dynamic range of the hydrophone should be close to the ADC of the instrument chain. Note that the actual dynamic range is still limited by the system self-noise and the maximum measurable undistorted sound.

2.2.7 System Calibration

The full measuring system shall be calibrated over the full frequency range of interest. [Hayman *et al* 2017] This includes the hydrophone, amplifier, filter, and analogue to digital converter. It is preferred that a full laboratory calibration is performed at minimum every 2 years.

The calibration of the hydrophones must be traceable to national or international standards and conform to IEC 60565 [IEC 60565-1:2020, IEC 60565-2:2019, IEC 60500:2017].

2.2.8 Field calibration checks

In-situ field checks should be undertaken before and after each deployment. This can be performed using two methods

- Hydrophone calibrator, consists of an air pistonphone that generates a known sound pressure level at a defined frequency inside a coupling chamber into which the hydrophone is inserted. Note that this method generally provides a field calibration check at only one frequency (typically 250Hz) but it allows the integrity of the entire system to be checked. [BS ISO 18406:2017]
- Use of electrical check calibration of the system components. If the hydrophone has an insert voltage capability, electrical calibration can be performed through signal injection in order to check the system electrical integrity. However it does not perform an acoustical check on the hydrophone element. [NPL 2014]

2.2.9 Summary of recommended performance specification

Performance Characteristic	Recommended Specifications	
	Explosion	Background noise
Frequency range:	20 Hz – 20 kHz	
Sensitivity:	Less than -200 re 1V/ µPa (for use at a minimum range of 1 km)	Between -185 to -165 dB re 1 V/µPa
Frequency response	Invariant with frequency (flat response) in the range 20 Hz to 20 kHz (to a tolerance of ±1 dB)	
Dynamic range:	System dynamic ranges of in excess of 60 dB are preferred. Analogue to digital converter (ADC) Minimum 16 bit resolution (nominal dynamic range 96 dB), Preferable 24 bit resolution (nominal dynamic range 144 dB)	
Signal to noise ratio	Minimum 6 dB level difference	
Directionality:	Omnidirectional to within +/- 2 dB up to 20 kHz	
Sampling frequency:	44.8kHz (for one-third octave levels required up to 20 kHz)	Twice the maximum frequency of interest (defined by the maximum hearing response of relevant receptors)

<table>
<tr><th rowspan="2">Performance Characteristic</th><th colspan="2">Recommended Specifications</th></tr>
<tr><th>Explosion</th><th>Background noise</th></tr>
<tr><td>Filtering:</td><td colspan="2">Any filter characteristics should be known and corrections applied (low pass and high pass filtering caused by instrumentation). Any low frequency roll-off in recorder performance due to high pass electronic filtering must be measured so that suitable corrections can be applied.</td></tr>
<tr><td>System self-noise:</td><td colspan="2">Ideally 6 dB below the lowest sound level.</td></tr>
<tr><td>Calibration</td><td colspan="2">Calibrated to traceable standard within the last 2 years</td></tr>
<tr><td>Data storage</td><td colspan="2">Raw data ideally stored in lossless format.
Any compression used must be reported, and uncompressed data must be recoverable before analysis.

Metadata to be stored: instrument calibration and ADC scaling factor, amplifier gains, sampling frequency and resolution</td></tr>
</table>

3. Deployment

3.1 Deployment Methodology

For measurement of underwater explosions, one or both of the following generic deployment methods should be adopted depending on available resource and conditions.

3.1.1 Static Deployment

A static deployment typically consists of hydrophone(s) connected to an autonomous recorder that can be moored at the bottom of the seabed to allow remote acoustic measurement in the water column. This system enables multiple units to be deployed at the same time in order to monitor the sound propagation at several fixed ranges simultaneously. This is considered a more cost-effective method for measuring underwater explosions if multiple ranges are required.

With regard to platform noise, a static bottom-mounted deployment is generally preferable to a surface deployment because the hydrophone is positioned away from the air/water boundary, thus minimising the effect of this pressure-release boundary on the sound field, and reducing parasitic signals from the influence of surface wave action. It also has the advantage that measurements may be safely made at range that is considered unsafe for vessels during a detonation operation.

Field deployment of a static system is typically more complex than a vessel based deployment, as it requires a mooring to be built and prepared prior to the field trial. Recovery requires either a surface buoy connected to a seabed anchor or an acoustic release system, which enables the recorder to be hauled to the surface.

3.1.2 Vessel based deployment

This involves deployment of hydrophone (either individually or in arrays) from a vessel, with the analysis and recording equipment remaining on the vessel, which can be either anchored or drifting. The method has the advantage that deployment can be quick and mobile, allowing flexibility to suit different operational changes. The risk of losing instrumentation is low, the data can typically be monitored as they are acquired and instrument settings can be adjusted in real time to provide the optimal setting for the required dynamic range to avoid signal saturation.

However, vessel based deployment can suffer from certain types of platform related noise [BS ISO 18406:2017]. As hydrophone is deployed in close proximity with a survey vessel, there is potential for parasitic signals to be produced. These possible sources of platform noise can include:

1) Flow noise
   Low frequency noise caused by the turbulent flow around the hydrophone.
2) Cable strum
   Noise caused by the action of current on the taut cable.
3) Surface heave
   Large amplitude, low frequency noise caused by the changes of hydrophone depth due to vertical motion of wave action.
4) Vessel noise
   This can be any source of noise originated from survey vessel, it includes the engine propeller, generator, echo sounder and other vessel machinery.
5) Mechanical noise

This includes any mechanical contacts in close proximity or direct on the hydrophone, for example mooring anchor chain, direct contact with sediment, or biological abrasion noise.

6) Electrical noise
   This typically caused by measuring system being powered by the vessel electrical main, causing electrical interference and noise.

Although platform noise is unlikely to mask the high amplitude signal from an explosion for measurements made close to the source, attempt should be made to minimize its influence and help improve the data quality for the data analysis. For guidance on how to minimize the above noise sources, see [BS ISO 18406:2017] and [NPL 2014].

In addition, a human presence is required for a vessel-based deployment, and this may not be possible if there is a likely encroachment within the safety exclusion zone of the EOD operation.

3.2 Hydrophone Deployment

3.2.1 Hydrophone depth

The hydrophone is to be positioned in the lower half of the water depth and at least 2 m above the seafloor. If hydrophones are to be deployed at two depths, these should be placed in the lower half of the water column ideally between ½ and ¾ of the total depth, ideally with the separation between hydrophones maximised.

3.2.2 Number of hydrophones

Clearly, one hydrophone at each measurement station is the minimum requirement. However where feasible, at least two hydrophones are recommended for the respective measuring location(s). This is to allow redundancy in the measurement and also provide flexibility when required to use multiple hydrophones of different sensitivity in order to measure high amplitude sound and low level background noise without signal clipping and distortion. The extra data collected at the same position also allow the spatial averaging of the acoustic data (assuming data from all hydrophones are good quality with no clipping) and assist in assessment of measurement uncertainty.

4. Acoustic measurement

4.1 General Remarks

When a UXO is detonated as part of an EOD procedure, it is acknowledged that there is only a single instantaneous event per detonation, thus repeated measurements as a function of time are not possible. Spatial sampling is typically limited by health and safety considerations (i.e. measurement must be clear of any safety exclusion zone) and other operational constraints (i.e. additional deployment vessel, deployment/recovery time) during the EOD operation. Thus, in this document emphasis is placed on the far-field sampling of the event to enable comparability of UXO measurement in a similar setting.

4.2 Data Sampling

In general, the measurement shall be chosen to satisfy at least one of the following requirements:

- Measurement at fixed location(s) to monitor the source output for comparison with other underwater explosion events.
- Measurement to assess the accuracy of predictions made from numerical models.
- Measurement for validation of models of source radiation mechanisms.
- Measurement to derive a source output metric (e.g. a source level)
- Measurement that allow comparison with a normative threshold level (i.e. NMFS guideline 2018)

It is acknowledged that measurements of underwater explosion are site specific and many parameters cannot be determined, such as the ordnance age, effective charge weight and seabed properties, etc. The objective is to obtain datasets that are as consistent as possible in order to aid the understanding of UXO explosion and its impact in the marine environment.

4.3 Recommended measurement locations

Recommendations are given according to the different scenarios.

4.3.1 Estimation of peak sound pressure at measurement location

UXO found in the open ocean can vary in type and size, and so the distance from the source of the chosen measurement location must be chosen carefully. It is recommended that before measurements are undertaken, an estimate is made of the peak sound pressure at the measurement location generated by the explosion. This estimate should be used to determine the required measurement system response (in particular, the dynamic range), an appropriate measurement set up should be chosen that can enable measurements to be carried out without clipping or saturation of the measured signal at the measurement range.

The peak pressure can be estimated for a given explosive type and location, according to the following

$$p_{pk} = k \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\alpha}$$

where

p_{pk} = peak sound pressure (MPa)

W = charge mass (kg)

R = distance from explosion (m)

k, α = shock and pressure coefficient

The shock and pressure coefficient are derived empirically. Details of the modelling of underwater explosion and the equivalent coefficients of different explosive type can be found in Appendix A.

4.3.2 Minimum and maximum range requirement

The minimum range for measurement is governed by two factors:

- safety considerations requiring all deployments and vessels to be outside the exclusion zone defined during the EOD operation;

- the dynamic range of the instrumentation used (governing the maximum acoustic signal that can be faithfully recorded).

The first consideration will determine whether vessel-based deployments are possible in the vicinity of the EOD operation but may also influence the ability to deploy static systems such as autonomous recorders. If there are groups of UXO located close together on the seabed, the size of the cluster may prevent deployments close to any one individual UXO. Ideally, the second consideration should not be an issue because the system performance may be designed to measure the estimated peak sound pressure at the location. However, in practice, a limited range of acoustic instrumentation may be available for use on any deployment, and the maximum recordable sound pressure for the instrumentation available may influence minimum range achievable.

In consideration of the above issues, the minimum recommended range from the UXO for any measurement location is 1 km. It is recommended that a measurement is made at 1 km range for all EOD clearances wherever possible (though it is accepted that there may be some operations where for reasons of safety or practicality, this may not be possible). In some situations, it may be possible to deploy a high dynamic range static measuring system closer than 1 km before the EOD operation begins (assuming there are no issues with vessel manoeuvrability or safety). However, even in such exceptional circumstances, a measurement should also be made at 1 km.

The measurement is best achieved using a bottom mounted static deployment but a vessel-based deployment may also be used (Figure 1). A vessel-based deployment at 1 km may be considered unsafe during the explosive ordnance disposal operation, in which case it is advisory to use static system deployed in advance of the EOD operation. The recommended 1 km range is based on a far field shock wave model of a small explosive charge [Aaron 1954], which predicts peak sound pressure for a given charge of equivalent TNT.

If the recommended range cannot be used due to excessive peak pressure or limitation of measuring instrumentation, it is acceptable to use an alternative range to ensure the full waveform to be captured without saturating or distorting the signal, provided requirements described in 2.2.9 can be satisfied.

The maximum range for a measurement station is recommended to be at least 10 km, and ideally 20 km. However, it is recognised that there may be practical limitations on the maximum range (for example, where deployments are limited to within the area of a specific offshore development).

4.3.3 Spatial configuration of measurements

The minimum number of sampling locations recommended in this document is **one single location**. Where operation is restricted by safety constraint and limited resources, this may be the only option. However, while even one good quality measurement is better than none, it is recommended that where possible, measurements are made at **three or more locations**. There are two options for the spatial configuration of measurement locations.

Measurements along a transect

A number of measurement stations are positioned in a straight line along a single azimuthal bearing from the UXO position, with the closest position no closer than that defined in 4.3.2. Such a strategy enables the propagation of the acoustic wave along a specified transect to be empirically estimated by determining the properties of the acoustic pulse as a function of range. It is recommended that (if possible) ranges are selected by at least an approximate tripling of distance relative to the 1 km minimum range (for example, say 1 km, 3 km, 10 km, etc.) in order to observe significant changes in sound pressure over long distances.

Measurements at fixed grid locations (along a variety of bearings)

Here, a number of fixed measurement stations are located along a variety of different bearings and at different ranges from the UXO. This measurement strategy is more suited to an EOD campaign where numerous UXO are to be cleared from an area, and where re-positioning of the measurement stations after each EOD clearance is not practical. Here the stations would be positioned on a grid in the vicinity around the UXO grouping, with the bearings and ranges to the stations varying for each UXO. The closest position to any UXO should still satisfy the requirements of 4.3.2.

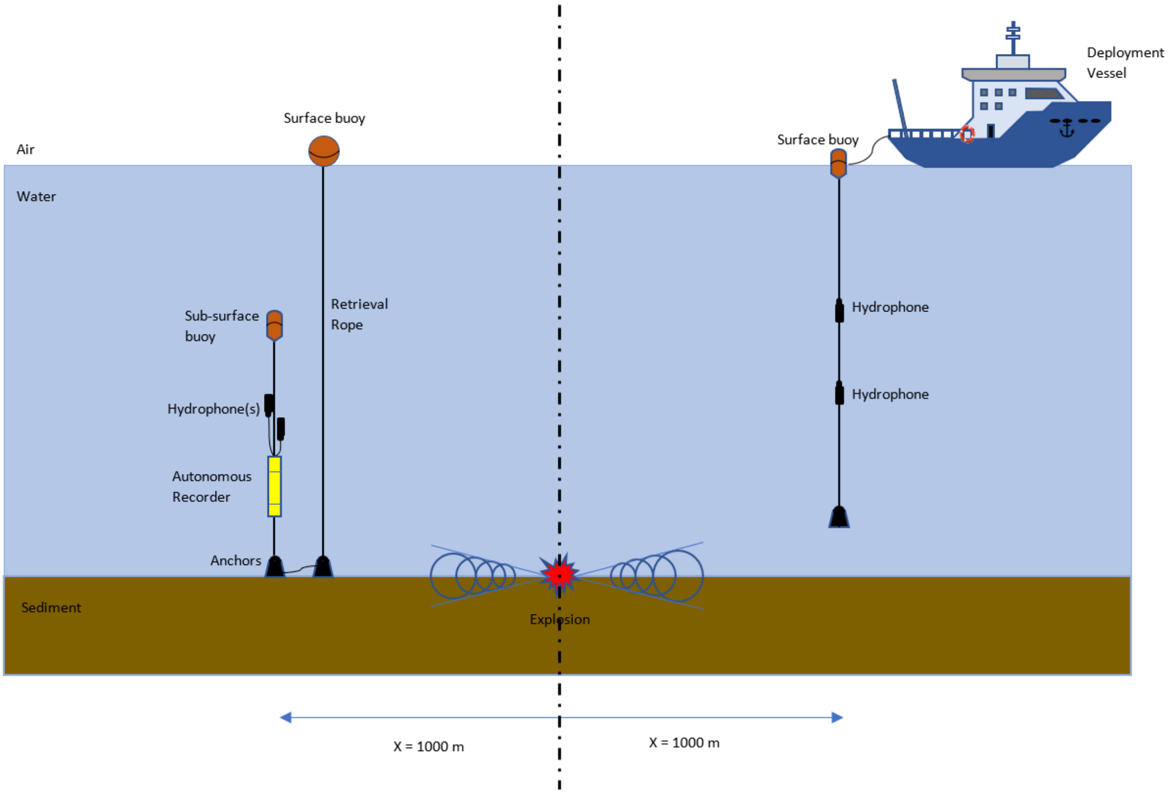

Figure 1 Deployment schematic of hydrophone. (Left) Moored static mooring using an autonomous recorder. (Right) Vessel based deployment. Note: diagram is not to scale.

4.3.4 Multiple explosions

In the case of multiple explosive sources closely located, forming an explosive cluster, it may be possible to position the measuring stations such that the bearings are approximately the same from the sources to the measuring stations, provided the explosives are close together. This negates the need to reposition the static deployments in order to satisfy the transect requirement whilst reducing potential operational errors.

Where a fixed grid of measurement stations is employed, the locations should surround the UXO cluster (the positioning of a station within the cluster being regarded as impractical). The minimum range of 1 km applies from the nearest explosive to the closest measurement station. The distances between the measurement positions and each explosive must be reported (see 4.4).

If a measurement is conducted using a single vessel based method, the vessel should be repositioned for each explosion to achieve the 1 km separation between the UXO and measuring station.

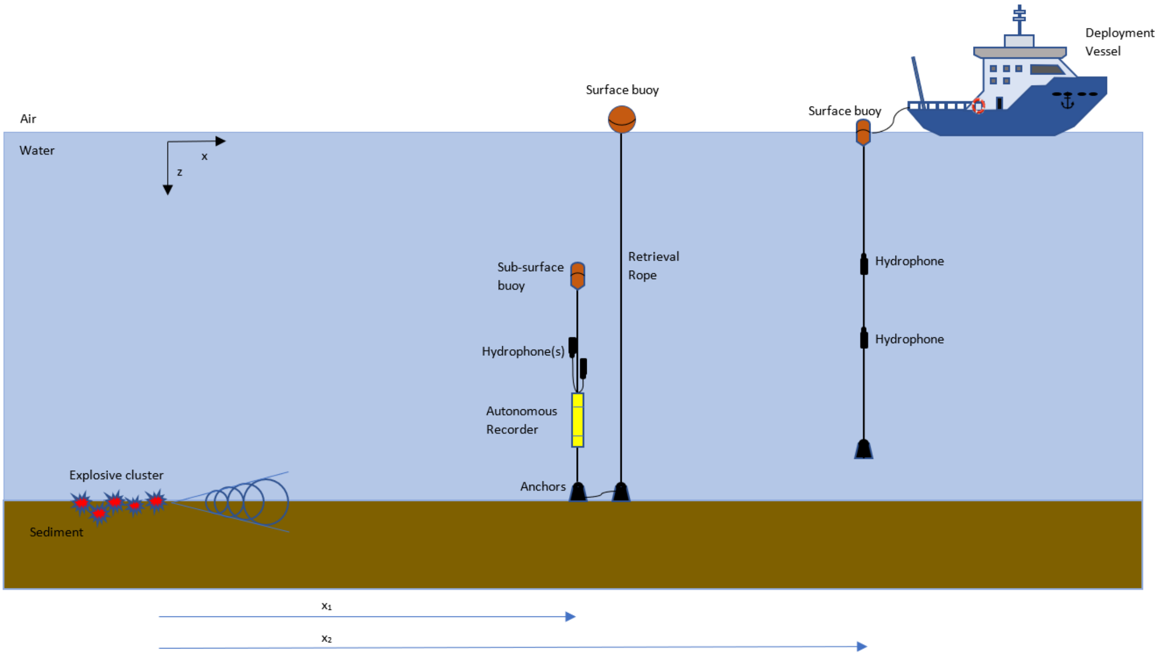

Figure 2 Schematic showing deployment set up for multiple explosion (not to scale)

4.3.5 Additional measurement locations

Depending on the monitoring requirement, a station can be located to monitor at the range where a specific exposure threshold is predicted to be exceeded for a specific marine species (for example for PTS), to ensure that the acoustic energy has been significantly attenuated by propagation loss. Where there are areas known to contain animals that are particularly sensitive, consideration should be given to locating a measuring station in the area of concern; this will help validating expectations and reduce uncertainties.

4.4 Distance measurement

It is likely that the deployment position will deviate from the desired range due to operational constraints or other environmental conditions such as weather conditions or current. The actual range from the explosion to the measurement locations must be reported with the results.

The distance measurement should be determined using latitude and longitude coordinates of the explosive location and measurement position. The GPS accuracy should be sufficient to determine the distance to within +/- 5 % [BS ISO 18406:2017].

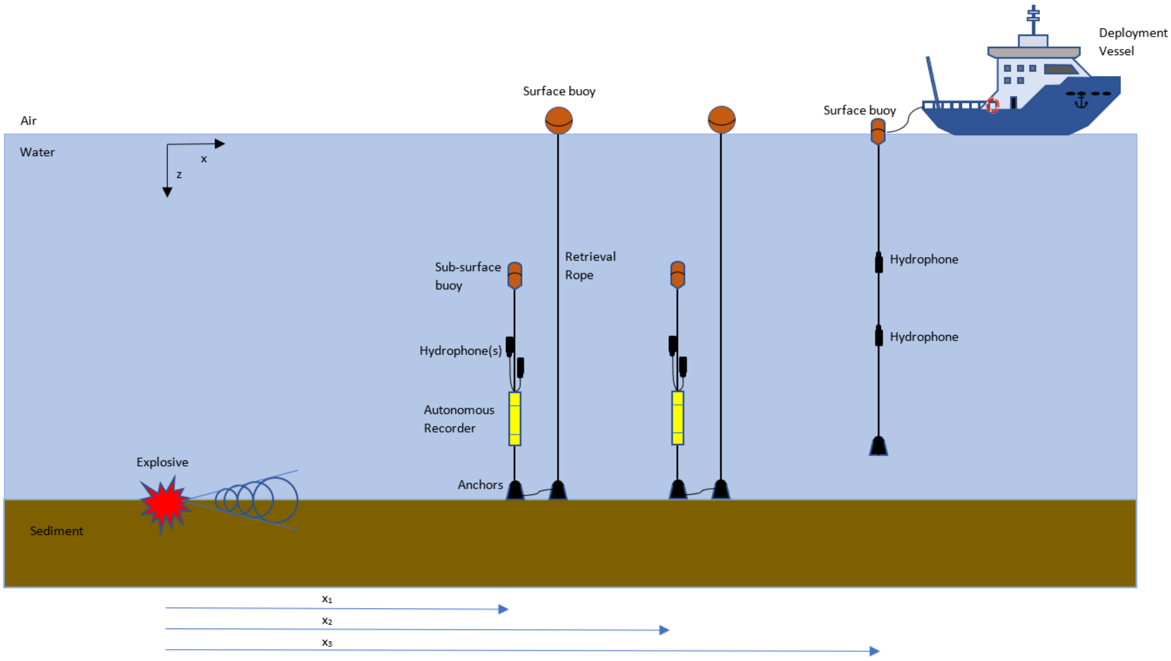

Figure 3 Schematic showing deployment set up with multiple measuring stations forming a sampling transect.

4.5 Depth Profile

To ensure comparability between different UXO measurement, it is important that acoustic data collected along a transect (or over a grid in a region) is obtained over a reasonably constant water depth (constant bathymetric profile) without any significant sudden changes in depth or strong bathymetric features, for example a strongly sloping bottom or sand bank. Ideally, any abrupt changes in the sediment type should also be avoided. These requirements may or may not be achievable, depending upon the location of the UXO. Especially when they are not achieved, accurate knowledge of depth profile (and sediment type) should be supplied together with acoustic data to help with propagation modelling.

4.6 Functional Configuration and Testing

An appropriate protocol for carrying out measurement, such as deployment method, functional test of equipment, system configuration, are to be established and followed for the selected measuring point. This is to enable early discovery of a problem; any sign of data artefacts can indicate problem with the measurement system. It is important to check for errors in the system configuration, such as electrical connection, signal quality and other sampling related settings [André *et al* 2011].

The functions of the hydrophone measurement chain shall be checked using an in-situ calibration (section 2.2.8) method. In addition, the means to visualize audio data in-situ on a computer screen can provide extra confidence that data are collected with the correct dynamic range and frequency bandwidth before the final deployment.

It is recommended in-situ calibration checks be carried out on all measurement systems prior of deployment, and after retrieval of the instrumentation.

4.7 Protection from damage/loss

The associated risk of damage is considerable higher when measuring underwater sound from an UXO. Loss of equipment/data can occur if the final deployment configurations are not selected carefully [EU TSG Noise 2014b]. This is a problem for all system but autonomous system is especially more susceptible to damages. The main dangers are potentially caused by the high-amplitude acoustic wave and excessive vibration acting on the air-filled bodies of many autonomous acoustic recorders. This can cause damages to the internal component of the recording system if not isolated properly. If the recorder body is damaged, it can cause water ingress and care should be taken to design the survey to avoid such damages. An adequate anchor should be used to militate against movement under the action of currents and withstand the abrupt vibration caused by the blast. The above damage is more likely for recorders placed very close to the UXO (within the first 2 km).

In addition to loss of equipment, there is also a risk of loss of data. This can result of significant cost as there is only one opportunity to record the underwater explosion. Vessel based deployment generally gives the advantage of instantly retrievable data and protects against data loss. However, for autonomous recorders with archival storage, the data is only available periodically after recovery. Thus such system must be thoroughly configured and tested (as recommended in section 3.6) before final deployment.

5. Data Processing and Acoustic Metrics

5.1 Conversion to sound pressure

The output of the acquisition system of the instrument measurement chain (hydrophone, preamplifier, ADC) is assumed to be a signal waveform consisting of a digitized time series expressed in digital counts and representing the signal detected by the hydrophone and recorded by the acquisition system. The data format is assumed to be a binary data file containing the digitized signals of the hydrophone recording obtained over a discrete time series, where t_i corresponds to the i^{th} point in the time series.

The data processing to convert the waveform data to sound pressure shall be conducted according to the following steps.

a) Identify the event in the waveform and read the segment of the data for analysis consisting of $N = T f_s$ points where T is the analysis window duration in seconds and f_s is the sampling frequency.

b) Confirm that data show no signs of “clipping” (overloading the maximum allowed amplitude of the measurement chain). This will be evident from data samples which reach the maximum or minimum value of the ADC.

c) If required, digital filters may be applied to limit the frequency content of the signal to the overall band of interest and to remove low frequency parasitic signals such as flow noise.

d) Convert the time waveform in the selected widow to a frequency spectrum expressed as frequency bands, either using Fourier analysis or via digital filtering. The frequency bands should be calculated as one-third octave bands.

e) If the system sensitivity is provided in analogue units of V/Pa or dB re 1 V/μPa, then the digitised signal must first be converted to a voltage signal before the sensitivity can be applied to the signal. In this case, convert the signal waveform to a representation of electrical voltage in volts, $V(t_i)$, by dividing by the sensitivity of the analogue to digital converter (ADC), where the digitizer sensitivity is the number of digital counts per volt (V^{-1}).

f) If the sensitivity response of the instrument measurement chain is uniform in the frequency range of interest, then a frequency-independent sensitivity may be used (a single value may be applied across the entire frequency range). In this case, the signal voltage waveform in volts, $V(t_i)$, may be converted to a sound pressure waveform $p(t_i)$ in pascals by dividing by the system sensitivity, M_s in V/Pa (assuming the system does not introduce any phase delay):

$$p(t_i) = V(t_i) \quad / \ M_s$$

g) If the response characteristics of the instrument measurement chain are not uniform in the frequency range of interest, then an appropriate frequency-dependent sensitivity shall be applied. If frequency-dependent sensitivity values are available from a suitable calibration, the sound pressure frequency spectra $P(f_i)$ shall be calculated from the voltage spectra V(fi) (obtained by taking the Fourier transform of $V(t_i)$) by dividing by sensitivity frequency response (the frequency spectral representation of the modulus (magnitude only) of the system sensitivity), $M(f_i)$

$$P(f_i) = V(f_i) \quad / \ M(f_i)$$

h) Determine the acoustic metrics to be calculated from the selected period of the sound pressure waveform (see section 5.2).

i) Perform further analysis of the calculated acoustic metrics for reporting of results.

5.2 Acoustic Metrics

Two acoustic metrics, peak sound pressure and sound exposure level (SEL) are considered here [**ISO 18405:2016**, **ISO 80000-8:2020**]. The following describes the procedure of calculating the relevant acoustic metrics for the acoustic pulse from the explosion event.

5.2.1 Peak sound pressure and peak sound pressure level

The peak sound pressure should be calculated for the acoustic pulse from the sound pressure waveform, this can arise from the compressional or rarefactional sound pressure and is sometimes referred to the zero to peak sound pressure.

The peak sound pressure, p_{pk}, is expressed in pascals (Pa) and calculated as the greatest magnitude of the sound pressure, $p(t_i)$, for the time duration of the acoustic pulse. This is given by

$$p_{pk} = \max_{t_0 \le t_i \le t_{100}} |p(ti)|$$

Where t_0 is the time at the start of the acoustic pulse, and t_{100} is the time at the end of the pulse.

The peak sound pressure level, $L_{p,pk}$, is expressed in decibels and it is given by

$$L_{p,pk} = 20 \log_{10}\left(\frac{p_{pk}}{p_0}\right)\, dB$$

Where the reference value, p_0, is 1µPa.

Note: The phase information in the signal can be distorted by a severely non-uniform frequency response in a measuring system or by filtering of the signal. For calculation of acoustic metrics which depend on the energy or power in the signal (eg SPL and SEL), this is not a problem. However, a non-uniform phase response may have a significant effect on time-domain metrics such as peak sound pressure. Typically, the system phase response in not known. For cases where the phase response is known and where the response varies significantly with frequency in the frequency range of interest, a deconvolution approach can be used to re-construct the time-waveform. Further guidance is given in [ISO 18406:2017].

5.2.2 Single pulse sound exposure level (SEL_{sp})

The single pulse sound exposure level, SEL_{sp}, should be calculated for the specific acoustic pulse as a broadband value with frequency covering at least bandwidth between 20 Hz and 20 kHz. To calculate the SEL corresponding to a specific acoustic event requires the SEL to be calculated over the pulse duration. This is analogous to the single strike SEL defined in ISO 18406.

The single pulse sound energy is calculated for the entire duration of the pulse from the time series, where f_s is the sampling frequency, and t_0 and t_{100} are the 0% and 100% sound exposure points. The values t_0 and t_{100} are the start and end time of the acoustic pulse [ISO 18406:2017, NPL 2014]:

$$E_{100} = \frac{1}{f_s} \sum_{i=t_0 f_s}^{t_{100} f_s} \{p^2(t_i)\}$$

The total broadband signal pulse sound exposure level, SEL_{sp}, in dB re 1 µPa^{2}s is given in

$$SEL_{SP} = 10 \log_{10} \frac{E_{100}}{E_{ref}}\, dB$$

where $E_{100} = E(t_{100})$ is the 100% sound exposure and E_{ref} is 1 µPa^{2}s.

The 0 % sound exposure point (t_0) is selected at the “start” of the acoustic pulse, just before the curve begins to rise, and the 100 % sound exposure point (t_{100}) just after the “end” of the pulse, where it levels off. This can be difficult to determine due to the variation in background noise preceding (and overlapping) the acoustic event, as well as the background noise following the event. Consequently, it may be necessary to identify these points subjectively [ISO 18406:2017, NPL 2014].

Note that if the first and second bubble oscillations are prominent, the integration time for SEL_{sp} shall overlap with these bubble pulses (see Figure A1 in Appendix A). In such cases, the SEL_{sp} may be obtained by integrating the entire acoustic pulse sequence which included the shock wave and the subsequent bubble pulses.

A one-third octave band analysis of the sound exposure level should be obtained by applying the above formulae to the time series after first digital filtering with one-third octave band filters (or using Fourier analysis). The one-third octave bands should be calculated using a base-10 is the method [IEC 61260-1:2014, ISO 18405:2017]. Note that the base-10 representation of a one-third octave band is also referred to as a “decidecade” [ISO 18405:2017, ISO 80000-8:2020].

Hydrophone calibration data are typically expressed at a succession of discrete frequencies, or in the form of a calibration curve. If the recorded data are already processed into one-third octave bands before the correction for hydrophone sensitivity is applied, the required calibration values are the mean sensitivities for each of the frequency bands.

6. **Reporting**

6.1 General

Whenever a measurement is undertaken, auxiliary data must accompany the acoustic measurement in order to aid the interpretation of the results. It is beneficial to record any auxiliary data that are relevant, as these can be correlated with the measured level during the analysis [BS ISO 18406:20].

6.2 Reporting requirement

The following describes the mandatory and other optional measurement for the relevant category.

Measurements	Mandatory	Optional
Operational	- Date/time of recordings - Hydrophone depths in the water column - Coordinates of UXO sources and hydrophone measuring stations - Water depth at measurement locations	- Sound speed profile of the water column - Wind speed - Significant wave height - Tidal state during measurement - Precipitation - Presence of other vessels (within 5 km radius, where data available)
Explosive Characteristic	- Identifier and coordinate of UXO - UXO physical size or charge size - Water depth at UXO location - Description of UXO (e.g. munition type, state of submergence, approximate age) - Method of detonation - Number of UXO	- Seabed type at the measurement locations (Folk sediment classification or similar is sufficient; the classification used should be stated) - Bathymetry data covering the transect or area between the measuring instrument to the explosion.
Deployment Configurations	- Measurement system description (including acquisition system type, bandwidth, system self-noise dynamic range, sampling frequency, etc.). - Data compression routine, if used. - Description/diagram of deployment method and configurations - Hydrophone specification (type, model, directionality, nominal sensitivity); - Calibration details (Calibration standard, dates and certificate)	- Field calibration methods and results.
Analysis	- Broadband peak sound pressure and peak sound pressure level. - Sound exposure level, including broadband and one-third octave band levels	- Pulse duration for the associated broadband pulse. - Peak compressional and peak rarefactional sound pressure level. - The signal to noise ratio calculated from background noise level - The waveform of the underwater explosion, including the bubble oscillations, in graphical form.

7. References

1. [Aarons, 1954] A. B. Aarons, “Underwater explosion shock wave parameters at large distances from the charge,” J. Acoust. Soc. Am. 26, 343–346 (1954)
2. [Aarons *et al* 1949] A. B. Aarons, Cotter, T.P., “Long range shock propagation in underwater explosion phenomena II” U.S. Navy Dept. Bur. Ord. NAVORD Rep 478, 1949
3. [André *et al* 2011] 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.
4. [ANSI/ASA S1.20-2012], Procedures for Calibration of Underwater Electroacoustic Transducers, American National Standard Institute, USA, 2012
5. [BIAS, 2016]. BIAS Standard for Noise Measurements, Background information and Guidelines https://biasproject.files.wordpress.com/2016/04/bias_standards_v5_final.pdf
6. [BS EN ISO 18406:2017], Underwater Acoustics – Measurement of Radiated Underwater Sound from Percussive Pile Driving, ISO (the International Organization for Standardization), Switzerland, 2017.
7. [BS EN ISO 18405:2017], Underwater Acoustics – Terminology, ISO (the International Organization for Standardization), Switzerland, 2017.
8. [BS EN ISO 80000-8:2020], Quantities and units - Part 8: Acoustics, ISO (the International Organization for Standardization), Switzerland, 2017.
9. [BS EN IEC 60565-1:2020] Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 1: Procedures for free-field calibration of hydrophones, International Electrotechnical Commission, Geneva, Switzerland.
10. [BS EN IEC 60565-2:2019] Underwater acoustics – Hydrophones – Calibration of hydrophones –Part 2: Procedures for low frequency pressure calibration, International Electrotechnical Commission, Geneva, Switzerland.
11. [BS EN IEC 60500:2017] Underwater acoustics – Hydrophones – Properties of hydrophones in the frequency range 1 Hz to 500 kHz, International Electrotechnical Commission, Geneva, Switzerland, 2017.
12. [BS EN IEC 61260-1:2014], Electroacoustics — Octave-band and fractional-octave-band filters, International Electrotechnical Commission, Geneva, Switzerland, 2014, (BS EN 61260-1:2014).
13. [Cheong et al 2020] Cheong, S-H., Wang L., Lepper, P. and Robinson, S. “Characterisation of Acoustic Fields Generated by UXO Removal - Phase 2 (Offshore Energy SEA Sub-Contract OESEA-19-107), NPL Report AC 19, June 2020.

14. [EU TSG Noise 2014], "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.
15. [Hayman *et al* 2017] "Calibration of marine autonomous acoustic recorders," Hayman G., Robinson S. P., Pangerc T., Ablitt J. Theobald P. D. OCEANS 2017 - Aberdeen, 2017, pp. 1-8. DOI: 10.1109/OCEANSE.2017.8084773
16. [NPL, 2014]. Good Practice 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.
17. [JNCC 2010] JNCC guidelines for minimising the risk of injury to marine mammals from using explosives, August 2010
18. [NMFS 2018] Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing, US Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR- 59, 167p
19. [Reid 1993] "The response of surface ships to underwater explosions." Reid, W.D. Australia DSTO Aeronautical and Maritime Research Laboratory.
20. [Robinson et al 2020] Robinson S.P, Wang L, Cheong S-H, Lepper P.A., Marubini F, Hartley J P. "Underwater acoustic characterisation of unexploded ordnance disposal using deflagration", *Marine Pollution Bulletin*, September 2020
21. [Snay 1956] "Hydrodynamics of underwater explosions", Snay, H. Washington DC.: Symposium on Naval Hydrodynamics, 1956
22. [Southall et al, 2019] "Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects", Southall B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P., and Tyack, P.L., *Aquatic Mammals* 2019, 45(2), 125-232. DOI 10.1578/AM.45.2.2019.125
23. [Urick 1983] "Principles of underwater sound", Urick, R.J. McGraw-Hill, New York, p. 423, 1983

[Weston 1960] "Underwater Explosions as Acoustic Sources", Weston, D. E. *Proceedings of Physical Society vol 76(2) p233.249, 1960*

Appendix A: Modelling of high order detonation

When explosive undergoes high order detonation, it creates a shock wave which the pressure can be approximated with exponential decay over time

$$p(t) = p_{pk} e^{\frac{-t}{t_0}}$$

Where $p(t)$ is the instantaneous pressure at time t after the beginning of the shock wave, p_{pk} is the peak pressure at time = 0, and t_0 is the exponential time constant.

[Urick 1983] summarizes Aarons' [Aarons *et al* 1949] semi-empirical work and provided a power law relationship between the peak pressure (µPa), charge weight (W) in kg and range (R), such that

$$p_{pk} = k \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\alpha}$$

Where k and α are determined empirically.

Based on this work, [Reid 1996] further developed the mathematical formulation based on different coefficients which depend on the type of explosive. It was observed that explosive type has a big influence on the peak pressure.

$$p(t) = K_1 \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_1} e^{-\frac{t}{t_0}}$$

Similarly the time constant in microseconds, can be expressed in respect to charge weight of TNT and range.

$$t_0 = K_2 W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_2}$$

Table A1 Equivalent coefficients for different type of Explosive [Reid 1996].

Coefficient	Notation	**HBX -1**	**TNT**	**PENT**	**NUCLEAR**
Shock wave	K_1	53.51	52.12	56.21	1.06 e^4
Pressure	A_1	1.144	1.18	1.194	1.13
Decay	K_2	0.092	0.092	0.086	3.627
Time constant	A_2	-0.247	-0.185	-0.257	-0.22

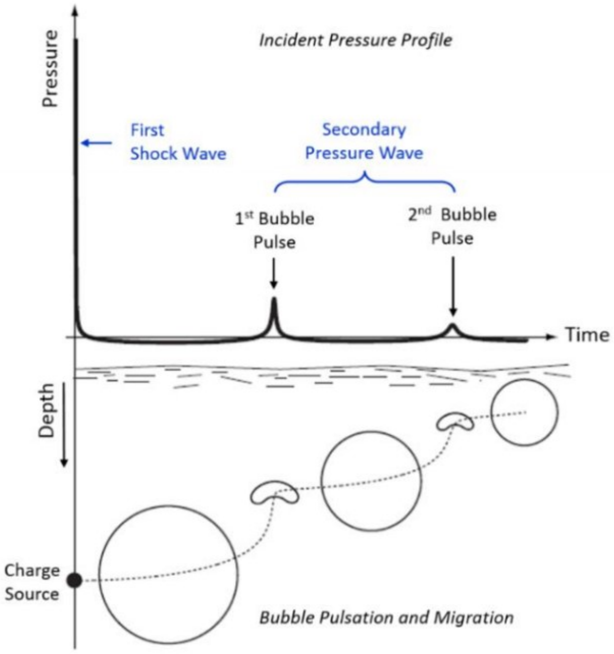

Figure A1 incident pressure of bubble migration process of underwater explosion ***[Snay 1956]***

After the detonation, a globular mass of gaseous material is formed, expands, and collapses creating a secondary pressure pulse. Successive oscillation creates additional bubble pulses with lower pressures, at shallower depths than preceding pulses. The time interval T_i in second between the detonation and first bubble pulses was derived empirically

$$T_i = \frac{0.48KW^{\frac{1}{3}}}{(d+10)^{\frac{5}{6}}}$$

where *K* = 4.36 for TNT and *d* is the depth below sea surface in m. Aaron [Aaron 1954] noted this empirical relationship for high explosives are valid up to ranges of

$$R_{max} = 793\ W^{\frac{1}{3}}$$

Appendix B: Peak pressure signal processing considerations

It is very useful to examine the effect of signal bandwidth on the peak for practical purposes. Figure B.1 shows a synthesised shock waveform based on the measured data of 10 kg charge explosion with a normalised peak. The shock waveform consists of a sharp rise to the peak with a time period of 6 µs, followed by an exponential decay using the time constant by Weston (1960). To account for slower decay of the waveform after the time constant, another two larger time constants were applied at $T = 2.2t_0$, and $T = 4.0t_0$. The blue line is for the synthesised signal. A number of low pass filters were then applied to the signal so that the peak values of the signal can be compared. The bandwidths are 3 kHz, 6 kHz, 12 kHz, 24 kHz, 48 kHz, 96 kHz and 192 kHz respectively. The difference between the original shock wave signal and low-pass filtered signals is shown in **Error! Reference source not found.**. It can be seen that the difference is less than 0.5 dB if the processing signal bandwidth is greater or equal to 12 kHz.

This information is useful in selecting frequency range both in setting the sampling frequency of a measurement device and for calculating channel response of a given underwater channel. The time required to run propagation models can be substantial for large distance such as 10's km over frequency range above 10's kHz. Use lower signal bandwidths with an acceptable error can reduce running time significantly.

Table B.1 Difference between original shock wave signal and low-pass filtered signals

Bandwidth (kHz)	3	6	12	24	48	96	192
Amplitude(dB)	-2.5	-1.0	-0.2	0.3	0.5	0.3	0.1

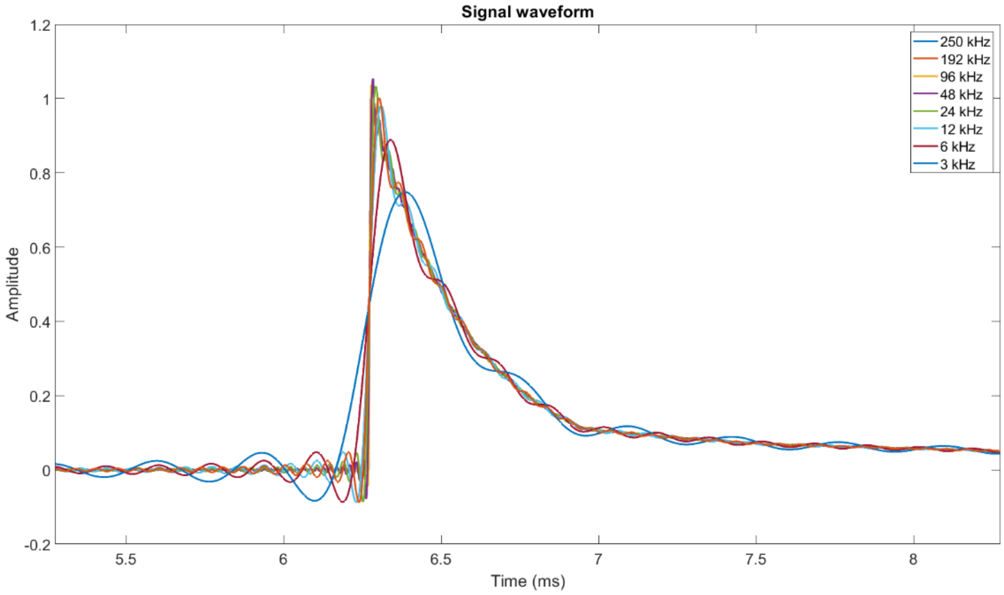

Figure B 1 Shock wave peak with different processing bandwidth