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TNO report

TNO 2021 R11210-A | **Final report**

Measurement procedures for underwater sound sources associated with oil and gas exploration and production activities

Date	October 2021
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Number of pages	69 (incl. appendices)
Number of appendices	2
Sponsor	IOGP JIP Sound and Marine Life
Project name	IOGP JIP Measurement Standards
Project number	060.22284Contract numberJIP22 III-15-13, Schedule No: 04 (III-17)
Contract number	JIP22 III-15-13, Schedule No: 04 (III-17)

Management summary

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Date	:	October 2021
Project nr.	:	060.22284
Report nr.	:	TNO 2021 R11210-A
Contract nr	:	Contract: JIP22 III-15-13, Schedule No: 04 (III-17).

This report is the result of Phase 2 of a two-phase project for the standardization of measurement, processing and reporting procedures for offshore oil and gas exploration and production-related sound sources. This project was carried out for the E&P Sound and Marine Life Joint Industry Programme of the International Association of Oil & Gas Producers (IOGP).

Phase 1 has resulted in the publication of a terminology standard, a data processing standard and a reporting standard. The aim of Phase 2 was to provide the oil- and gas industry with standardized procedures for measuring underwater sound radiated by relevant sources in the operational area, with limited hindrance on operations. The results of these measurements should allow for characterization of the sources in a clear manner, comparable between independently carried out measurements, and suitable as input for environmental impact assessments.

This Phase 2 report describes measurement procedures for seismic acquisition sources (type A), high-resolution geophysical survey sources (type B) and production activity sources (type C).

Citation:
de Jong CAF, HWJ Jansen, MB Halvorsen, DE Hannay, MA Ainslie, RG Racca. 2021. Measurement procedures for underwater sound sources associated with oil and gas exploration and production activities. Prepared for E&P Sound and Marine Life Joint Industry Programme. TNO 2021 R11210-A. Contract: JIP22 III-15-13, Schedule No: 04 (III-17). Pp 68.

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Abbreviations

ADC	analogue to digital converter
ANSI	American National Standards Institute
ASA	Acoustical Society of America
CPA	closest point of approach
CSA	CSA Ocean Sciences Inc., USA
CTD	conductivity, temperature, and depth
E&P	exploration and production
ESL	energy source level
GPS	global positioning system
HRG	high resolution geophysical (surveys)
IEC	International Electrotechnical Commission
IOGP	International Association of Oil and Gas Producers
ISO	International Organization for Standardization
JASCO	JASCO Applied Sciences, Canada
JIP	(Sound and Marine Life) Joint Industry Programme
NPL	(UK) National Physical Laboratory
PL	propagation loss
PSG	E&P Sound and Marine Life JIP Project Support Group
psu	practical salinity unit
rms	root-mean-square
SEL	sound exposure level
SL	source level
SNR	signal to noise ratio
SPL	sound pressure level
TAW	temporal analysis window (interval of time containing multiple temporal observation windows over which statistics of the sound field metrics are calculated)
TOW	temporal observation window (interval of time within which metrics of the sound field are calculated or estimated)
TNO	Netherlands Organisation for Applied Scientific Research
UNH	University of New Hampshire

1 Introduction

1.1 Background

The International Association of Oil & Gas Producers (IOGP) promotes the use of standard procedures for underwater sound measurements for activities related to offshore oil and gas exploration and production (E&P). Under its Sound and Marine Life Joint Industry Programme (JIP) (http://www.soundandmarinelife.org/), a consortium consisting of TNO (Netherlands), CSA (USA), UNH (USA) and JASCO (Canada) and independent consultants produced a series of reports describing standard procedures for:

1. Terminology, report TNO 2016 R11076 (Ainslie et al., 2018a)
2. Data processing, report TNO 2017 R10022 (Ainslie et al., 2018b)
3. Reporting, report TNO 2016 R11188 (Ainslie et al., 2018c)

In February 2018, the IOGP awarded a contract for the development of “Standard Procedures for Underwater Noise Measurements for Activities Related to Offshore Oil and Gas Exploration and Production. Phase 2: Measurements for underwater sound sources associated with seismic acquisition, high-resolution geophysical surveys and production activities”.

1.2 Objective

The aim of this second phase was to provide the oil- and gas industry with standardized procedures for measuring underwater sound radiated by relevant sources in the operational area, with limited hindrance on operations. The results of these measurements should allow for characterization of the sources in a clear manner, comparable between independently carried out measurements, and suitable as input for environmental impact assessments.

Caution: in the event that procedures cannot be thoroughly followed, it is imperative that all deviations from the standard be thoroughly documented and reported. The importance of following the standard is the provision of comparability between studies and results.

1.3 Scope

This report describes standard procedures for measuring, analyzing, and reporting the underwater sound radiated by the following three underwater sound source types:

- **Type A** sources: used for geophysical exploration surveys (“seismic acquisition”); typically, low frequency systems for profiling sub-bottom structures, usually towed, such as airgun arrays, sub-bottom profilers, or marine vibrators;
- **Type B** sources: used for high resolution geophysical (HRG) surveys (e.g., multi-beam echo sounder, side-scan sonar); and
- **Type C** sources: associated with production platform activities, such as pumping and drilling, where appropriate treated as a single composite source. In contrast with the A and B source types, type C sources are stationary during the measurements.

The procedures are applicable for measurements of the underwater sound of these sources in or close to operational conditions, for which the measurement equipment is to be deployed in the operational area, with limited impact on operations.

The procedures build upon the terminology, data processing and reporting standards developed under Phase 1 (see § 1.1). The measurement procedures describe requirements for selection of equipment, calibration, placement in depth and range, sampling rates, and operational measurement procedures for the three source types. Signal analysis methods are specified, as well as reporting content and formats for the acoustic results and relevant metadata.

The scope of this report is limited to providing standardized procedures for measurements of sound pressure, for the purpose of source characterization. It does not include procedures for measurement of sound particle motion. This relatively new measurement technique is addressed in the Interim Best Practice Guide for Underwater Particle Motion Measurement for Biological Applications (Nedelec et al., 2021).

The source characteristics based on sound pressure are expressed in different acoustic metrics, depending on the nature of the sound pressure field (continuous or impulsive). Where possible, procedures are provided to express the source characteristics in terms of an appropriate source level, independent of the environment in which the measurements are taken. For some sources, especially for type C sources in close contact with the seabed, source level cannot be defined (Ainslie et al., 2014, 2020). Therefore, for these types of sources and situations, characterization is described in terms of radiated noise level (which is obtained by scaling with the distance at which the measurements were taken) instead of source level (which is obtained by adding propagation loss (PL) to the measured sound pressure level).

Characterization of the sources in terms of a full coherent source waveform, facilitating full reconstruction of the transmitted waveform, including phase information, is considered to be achievable only under carefully controlled conditions, similar to those for the collection of the Svein Vaage data set (Vaage, 1983; Prior et al., 2019). Such measurements, whether for arrays or single source elements, are outside the scope of this project.

The procedures have been developed on the basis of an initial literature review of existing methods (de Jong et al., 2019), combined with the experience of the consortium. The literature review revealed that there was a fair degree of commonality in reported measurements of airgun arrays (type A) and HRG sources (type B), but very limited commonality in reported measurements of oil and gas production activities (type C). Very few reports or publications included all relevant parameters.

Achieving consistency in measurements for underwater sound sources associated with seismic acquisition, high-resolution geophysical surveys and production activities depends strongly on being very precise in nomenclature and documentation of the various choices made concerning measurement geometry, instrumentation, and processing. We realize that being very precise sometimes requires sacrificing brevity and simplicity of expression. Therefore, we have added comprehensive checklists to relevant chapters.

2 Terms and definitions

This report follows ISO 18405:2017 of the International Organization for Standards (ISO) and the terminology described in the Phase 1 Terminology report (Ainslie et al., 2018a). Detailed acoustical terminology used in this report is provided in Appendix A.

The scope of this section is to describe language used to characterize sources (type A, B, C) and signals (pulse, nonpulse and continuous). The association of a particular source with one of these three source types is based mainly on its frequency band and corresponding directivity. This association with source type has implications for the appropriate measurement (Chapter 5) and processing (Chapters 6 and 7) procedures.

Criteria for determining to which source type (A, B or C) a given source belongs are described in § 2.1. The selection of source type for borderline cases might be a pragmatic one (if three out of four sources to be tested are clearly type B and the fourth is borderline then it could be simpler to use type B processing for all four sources).

Criteria for determining which signal type (pulse, nonpulse or continuous) is produced by a given source are described in § 2.2. The selection of signal type for borderline cases might be a pragmatic one (if three out of four signals to be tested are clearly pulses and the fourth is borderline then it could be simpler to use pulse processing (§ 6.2) for all four sources).

2.1 Sound source types

2.1.1 Type A sources (geophysical exploration surveys)

The purpose of these sources is to examine the sediments and composition deep into the sea floor. More specifically, these sources are used typically for geophysical exploration surveys (commonly referred to as “seismic” surveys), but they may also be used for higher resolution studies of near-seafloor faulting and gas presence in sediments. The sources are typically mounted on or towed by a moving platform. These source types include low-frequency pulse or short-duration signal sources, typically with most energy emitted at frequencies below 1 kHz.

Type A sources include airgun arrays, water guns, sparkers, boomers, and sub-bottom profilers, with signals that are typically categorized as pulses (see § 2.2). Signal durations of these pulses at the source are typically less than 125 ms and signal repetition periods are typically greater than 1,000 ms.

Also included as type A sources are marine vibrators and other low-frequency sources with signal duration and repetition periods of a few seconds. These signal types are categorized as “nonpulse” or “continuous” because of their more gradual variations in amplitude.

In this report the terms “type A” and “seismic” sources are used interchangeably.

Type A sources typically have most acoustic energy below 1 kHz and a repetition rate below 1 Hz. Their low frequency leads to a large beamwidth.

2.1.2 *Type B sources (geophysical engineering surveys)*

The purposes of geophysical engineering surveys are highly varied and include mapping the sea floor, understanding the sea floor composition, rare-mineral locating, mapping the water column and processes within the water column, identifying shallow gas and gas seeping from the sea floor, observing phytoplankton and zooplankton migrations, acoustic positioning and more. These sources are typically mounted on or towed by a moving platform. These surveys are performed with active sonar-like sources, which output sound signals and measure the returning echoes. Type B includes active sonar-like sound sources classified as HRG sources, which are most often used by hydrographic surveyors, as well as echosounders (also known as depth sounders, or depth finders), which are used on most vessels for navigation purposes. Type B sources typically transmit either nonpulses, or pulses with most energy at frequencies above 1 kHz.

Type B sources exclude geophysical exploration sources, categorized as type A sources with pulse signals (see § 2.2), but include nonpulse low-frequency HRG sources such as some sub-bottom profilers.

There are broad differences between many types of HRG sources, but a primary difference pertains to the frequency range, from below 100 Hz to 1 MHz or higher. Some sources, depending on the selected operational signal frequency range may qualify for more than one measurement paradigm. The user will need to discern the best measurement paradigm for their equipment and project in which to characterize the signal sound pressure waveforms.

For the purposes of this standard, only frequencies of 200 kHz and below are addressed, as this upper frequency is considered to be the limit for potential auditory impacts (Deng et al., 2014; Ketten, 1998; Mann et al., 2001; Mooney et al., 2012). Type B sources with an operational frequency above 200 kHz may still have relevant signal output at frequencies (<200 kHz) of interest for environmental impact, hence these are not necessarily excluded, in fact their subharmonics should be accounted for and reported.

Type B sources typically have most acoustic energy at frequencies above 1 kHz and a repetition rate above 10 Hz. The high frequency is typically associated with a narrow beam, which places constraints on the measurement procedure. The processing required for back-propagation to a source property also depends on frequency.

HRG Flexibility

HRG sources have extreme flexibility from the extensive combinations of user control and operational settings. The combinations are based on project needs, operational settings, deployment options, and steer-angle range. The HRG sources have a transmitted beam and a received beam, for which only the transmitted beam is of interest to this measurement standard. Properties of the transmitted beam are the beam pattern, steer direction, and sidelobe level, likely in two different angular directions; typically along track and cross-track.

Obtaining HRG information that is useful is dependent upon the extensive combinations (mentioned in previous paragraph) and the skill of the HRG operator. Because of the extensive combinations, documentation of all equipment settings and source geometries when performing an in-field measurement is important. It is recommended that the 'worst case' acoustic scenario specific to that project be measured in the field to characterize and report the signal sound pressure waveforms. Following is a list of influences and adjustments that highlight the flexibility of HRG operations (the list is not all inclusive):

Project/environmental influence
- Goal/project purpose;
- Water depth;
- Sediment type;
- Vessel speed;
- Sound speed profile.

General operational settings (each system has different adjustable parameters)
- Frequency band;
- Signal signature (frequency modulated / constant wave; envelope, cycles, pulse duration);
- Signal repetition rate (signal repetition period);
- Power level (watts; joule);
- Resolution;
- Swath width (beam focus);
- Deployment depth.

Deployment Options
- Over the side mounted (usually mounted onto a pole);
- Tow-fish deployment (variable depth);
- Hull mounted into a vessel hull;
- Deployment orientation,
  - steer angle (angle at which the source is directed).

2.1.3 Type C sources (production activities)

In contrast with type A and B sources, for which underwater sound production is essential for the operation and under control of the operator, type C sources produce underwater sound as an unintended by-product of their activity. The addressed type C sources are considered to be static underwater sound sources associated with production platforms, such as pumping and drilling, where it is appropriate to be treated as a single composite source. Published studies suggest that vessel activities near platforms and also dynamic positioning activities of floating platforms can contribute significantly to ambient sound levels, hence these can be included. Measurements of type C underwater sound sources are aimed at monitoring the radiated sound in the area of operation and identifying the contributions to the total sound field from different sound-producing activities and different radiating components of the source. This approach is similar to the engineering method for airborne sound power levels of multisource industrial plants (ISO 8297). Measurements are taken at distances where all individual sources within the platform can be approximately treated as a single point source at the geometrical center of the type C source.

Type C sources are typically stationary sources that produce underwater sound as an unintended byproduct of their activity.

2.2 Guidance on characterizing sound source signals

We recognize that consensus has not been achieved on a formal classification of signals as pulse, nonpulse and continuous. This section provides some guidance on making this characterization. Users of this standard are able to use alternative criteria for characterizations as deemed appropriate.

The recommended measurement procedures are intended to characterize and report the signal sound pressure waveforms. The standard defines analysis of these waveforms to calculate a variety of sound metrics; however, the source characteristics based on sound pressure will depend on the nature of the source output signal.

Sound sources are categorized as ‘pulse’, ‘nonpulse’ or ‘continuous’ according to the duration and repetition rate of the acoustic signal they produce.
A simplification for categorizing a signal into one of the three signal types ‘pulse’, ‘nonpulse’ and ‘continuous’ is provided. These three signal types are defined according to the signal duration (τ) and the silence duration ($T - \tau$), with T the signal repetition period, see Figure 1.

If the signal repetition rate (ν) is known, the signal repetition period (T) can be calculated using

$$T = \frac{1}{\nu}$$

If the silence duration is sufficiently large ($T - \tau > 1000\ \mathrm{ms}$), it is useful to characterize each signal independently of all other signals in a signal train. In this situation, the pulse versus nonpulse characterization by Southall et al. (2007) holds (red shading, Table). Specifically, a signal whose duration exceeds 1000 ms is likely to be a nonpulse whereas one shorter than 125 ms is likely to classified as a pulse. If the duration of the silence is short ($T - \tau < 125\ \mathrm{ms}$), the individual signals merge after temporal averaging, and the signal is then considered continuous (yellow shading, Table).

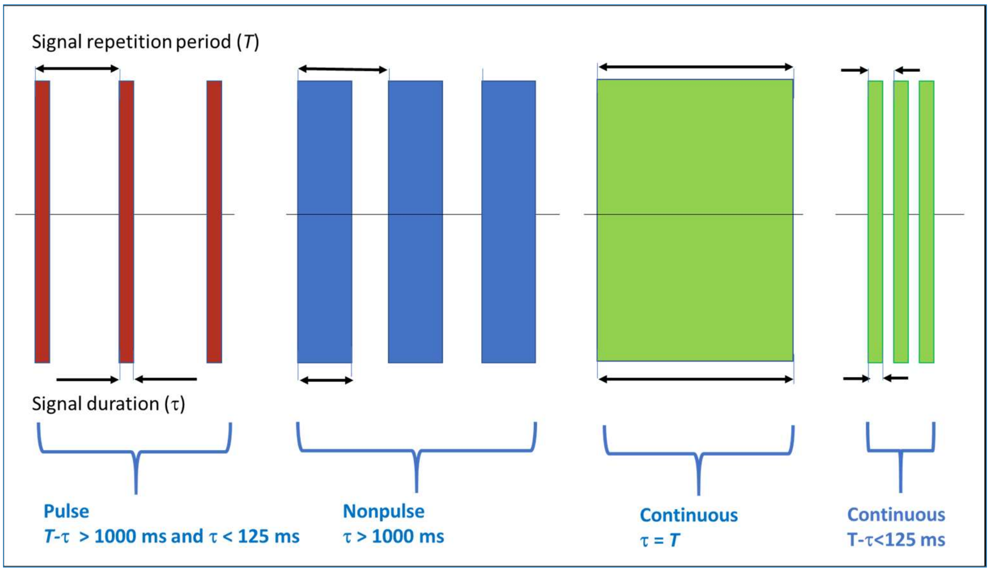

Figure 1 Schematic representation of signals, with different signal repetition periods (T) resulting in classification as either pulse, nonpulse or continuous signal. See also Table .

Table 1 Categorization of signals as pulses (short duration signals with a long inter-signal interval), nonpulses (long duration signals with a long inter-signal interval) and continuous signals (signals with a short or non-existent inter-signal interval). The grey areas represent signals that are not clearly in one category or another. In these grey areas the most appropriate choice of processing (see Chapter 6) might be determined by practical considerations. See also Figure 1.

Inter-signal interval	Signal duration τ < 125 ms	125 ms < τ < 1000 ms	Signal duration τ > 1000 ms
$T-\tau < 125$ ms	continuous	continuous	continuous
125 ms $< T-\tau < 1000$ ms	user-defined	user-defined	user-defined
$T-\tau > 1000$ ms	pulse	user-defined	nonpulse[1]

2.3 Source level, sound pressure level and propagation loss

Source level (symbol L_S) is a property of an underwater sound source, closely related to the level of the acoustic radiant intensity of that source (see ISO 18405 for a formal definition). Sound pressure level (symbol L_p) is a property of the sound field resulting from the presence of one or more sound sources, defined as the level of the mean-square sound pressure (see Appendix A.1 and ISO 18405).

If there is one and only one sound source contributing to the sound field, source level (SL) and sound pressure level (SPL) are linked via propagation loss (symbol N_{PL}), defined as the difference between SL and SPL at distance x

$$N_{\mathrm{PL}}(x) = L_{\mathrm{S}} - L_p(x) \qquad \text{Equation 1}$$

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[1] A long signal could have a short rise time and in principle be categorized as a pulse according to Southall et al. (2007). For the purpose of this document, the rise time is assumed to be unknown, and the choice between pulse and nonpulse is made on the basis of signal duration alone.

Sometimes SL is referred to as the SPL either “at 1 m” or “back-propagated to 1 m”. Neither statement would be correct (Ainslie 2010, p536). Instead, SL can be calculated from SPL and PL (assuming both are known), by rearranging Equation 1 in the form

$$L_{\mathrm{S}} = L_p(x) + N_{\mathrm{PL}}(x). \qquad \text{Equation 2}$$

A correct statement is therefore

$$L_{\mathrm{S}} = L_p(x_{1\mathrm{m}}) + N_{\mathrm{PL}}(x_{1\mathrm{m}}), \qquad \text{Equation 3}$$

where $x_{1\mathrm{m}}$ represents a position at a distance of 1 m from the nominal source position (which would need to be clearly specified for PL to make sense in the near field). For a source whose dimensions are small compared with 1 m, the PL at 1 m is approximately 0 dB re 1 m^2, and in that situation, SL and SPL are numerically equal (though they are still not equivalent, as they have different reference values). For a large source, such as an airgun array, PL in the near field of the source is larger than 0 dB re 1 m^2, implying that SL is larger than SPL.

Far away from a large sound source (in its acoustic far field) and neglecting the effects of nearby seafloor and sea-surface interface reflections, the mean-square sound pressure is inversely proportional to x^2, and this region is known as the region of “spherical spreading”. In the spherical spreading region, PL simplifies to

$$N_{\mathrm{PL}}(x) = 10 \log_{10} \frac{x^2}{1\ \mathrm{m}^2}\ \mathrm{dB}, \qquad \text{Equation 4}$$

This equation is valid in the acoustic far field, where the sound behaves as if radiated from a point source. It is not valid at 1 m from a large sound source.

As an example, consider an airgun array comprising 20 identical individual airguns, each with a zero-to-peak source level of 230 dB re 1 $\mu\mathrm{Pa}^2\ \mathrm{m}^2$. If the airguns are fired simultaneously, the combined source level of the array is then 256 dB re 1 $\mu\mathrm{Pa}^2\ \mathrm{m}^2$. At one meter distance from one of the individual airguns, the zero-to-peak sound pressure level is approximately 230 dB re 1 $\mu\mathrm{Pa}^2$, implying that the PL at that position is -26 dB re 1 m^2, so one would make an error of 26 dB at this position if one erroneously assumed Equation 4 applied close to the source. When one wishes to estimate SPL close to large sources like multi-airgun arrays, the SL of the full array may be less useful than the SLs of the individual airgun elements, which can be used to calculate each airgun’s individual contribution to SPL.

3 Instrumentation

The instrumentation selection for the underwater sound pressure measurements for activities related to offshore oil and gas exploration and production follows the recommendations from the NPL Good Practice Guide (Robinson et al., 2014) produced by the National Physical Laboratory (NPL). It is also consistent with the ‘Interim Best Practice Guide for Underwater Particle Motion Measurement for Biological Applications’ (Nedelec et al., 2020).

A typical modern system for measuring underwater sound pressure consists of the following components:
- hydrophone(s);
- preamplifier(s);
- frequency filter(s);
- analogue to digital converter(s) (ADC);
- digital recording system.

This chapter summarizes the requirements for selecting these components.

3.1 Selection of hydrophones and preamplifiers

Hydrophones are transducers that convert underwater sound pressure to an electrical signal. Most hydrophones are based on piezoelectric ceramic elements that produce an electric charge (in picocoulomb) proportional to the sound pressure (in pascal). Ideally, the hydrophone contains a preamplifier, that converts the charge signal to a voltage signal, as an integral part. This reduces the effects of cable capacitance and electrical noise contamination on the measured signal.

The hydrophone sensitivity, expressed in volts per micropascal (V/µPa) or in digital counts per pascal for digital hydrophones, needs to be considered relative to the expected signal strength.

It shall be low enough to avoid overloading the recording system (clipping), and high enough to yield sufficient signal to noise ratio (SNR) against electronic system noise for low amplitude signals. 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 range of interest.

The dynamic range of sound levels from the sources to be measured can be large. If the hydrophone-preamplifier combinations with broad bandwidth cannot fully cover the required dynamic range, two channels at the same location can be used, with different sensitivity.

The hydrophone and preamplifier must have linear response to amplitude and phase of the pressure – i.e., a fractional increase in applied pressure must result in the same fractional increase in output voltage through the full specified dynamic range of the hydrophone.

Hydrophones shall be selected to be suited for the environmental conditions (temperature and static pressure) at the measurement location.

Hydrophones shall be calibrated, traceable to national or international standards and conform to IEC 60565 of the International Electrotechnical Commission (IEC). It is preferred that a full laboratory calibration is performed at minimum every 2 years.

The hydrophone sensitivity should be preferably uniform ('flat' within a tolerance of ±1 dB) across the frequency range of interest (§ 5.2), and the hydrophone directivity should preferably be omnidirectional (to within ±1 dB) in the full frequency range. It is desirable to select a hydrophone with a resonance frequency above the upper limit of the frequency range of interest.

However, even high-quality hydrophones may have sensitivity and directivity variations over the frequency range of interest and these variations shall be taken into account for calculating received sound metrics (§ 6.5)

3.2 Selection of frequency filters

Where appropriate, the measurement system should include frequency filters before digitization, to:

- prevent aliasing, by means of a low pass filter designed to restrict the frequency content of the signal to below the Nyquist frequency of the recording system;
- reduce the influence of low frequency noise from flow, and surface motion, by means of a high pass filter.

If any of the above filters are used in the system, their characteristics shall be taken into account for calculating received sound metrics (§ 6.5).

3.3 Selection of recording system

The digital recording system's internal sampling rate, at a minimum, needs to exceed the Nyquist rate (twice the signal's maximum acoustic frequency). For example, the maximum frequency of 56.2 kHz (§ 5.2) requires a minimum internal sampling rate of 113 kHz. If there is significant signal content expected above the frequency range of interest, this should be reduced by the application of either an analogue anti-aliasing filter before the ADC or higher internal sampling rate (oversampling), so that a nearly ideal digital filter can cut off aliasing. The 24-bit digital acquisition systems provide a high dynamic range and should be employed unless careful matching of 16-bit systems with hydrophone analogue dynamic range can be performed. The voltage input range of the ADC must exceed the maximum voltage provided by the preamplifier to avoid signal clipping and distortion. The data format used to store the data should be lossless (no data compression).

3.4 System calibration

The frequency-dependent calibration characteristics of the complete measurement system, including hydrophones, amplifiers, cables, filters, ADC and recording system shall be determined, either by measurement in controlled conditions, or by superposition of the measured characteristics of the system components.

Additionally, the system calibration should be checked by an *in-situ* test just before and after deployment, and in between any repeated deployments, to make sure that the system is functioning as expected at the time of measurements. This can be done with a commercially available hydrophone-calibrator, which provides the hydrophone with a signal of known amplitude at a single-frequency (commonly at 250 Hz). A recording of this test signal should be compared with the controlled calibration to ensure consistency as well as help to validate scripted analysis routines.

System electrical self-noise should be checked prior to deployment of the hydrophones. For vessel-based deployments, electric noise and ground loop effects should be eliminated, by proper shielding and grounding of the measurement system and by switching off all unnecessary equipment.

3.5 Instrumentation checklist

Follow the NPL Good Practice Guide (Robinson et al., 2014)

Hydrophone

1. Appropriate hydrophone sensitivity;
2. At least 6 dB signal to noise ratio;
3. Flat amplitude response across the band of interest;
4. Omnidirectional;
5. Linear pressure to voltage response of hydrophone and amplifier;
6. Broadband frequency response of the hydrophone, amplifier, and filter;
7. Sensitivity and directivity variations to be accounted for.

Recording system

1. The Nyquist frequency of the recording system should exceed the maximum acoustic frequency of the signal;
2. Analogue anti-aliasing filter before ADC;
3. Oversample signal;
4. 24-bit digital acquisition systems preferred over 16-bit;
5. Measure and report self-noise.

Calibration

1. Calibrate hydrophones;
2. Recording system;
3. Whole system;
4. In-field validation with a hydrophone-calibrator;
5. In-field recording of the calibration signal.

4 Sensor deployment

Hydrophones can be deployed either from a static mooring that is anchored to the sea floor or from a surface vessel or surface buoy. The most appropriate deployment depends on various factors and will have to be selected on a case-by-case basis.

Factors to consider are:

- positioning of the hydrophones according to the required measurement geometry (Chapter 5);
- number of simultaneous hydrophone deployments;
- duration of the deployment and number of redeployments during the measurement campaign;
- deployment noise (vessel noise, mechanical noise, flow noise, cable strum, surface wave action);
- unobstructed line-of-sight between hydrophone and sound source.

A bottom-mounted deployment is generally preferable to a surface deployment to minimize interference signals from the influence of mooring movements from surface wave action, to keep the hydrophone away from the pressure-release water-air surface, to maintain constant position, and to minimize disturbance by surface vessels. Water flow noise on hydrophones should be minimized using acoustically-transparent flow shields.

For vessel-based deployments, the analysis and recording equipment may remain on the vessel or be suspended below surface buoys either anchored or drifting. However, steps should be taken to minimize supporting vessel noise. Deployments undertaken from a vessel shall be made under conditions as quiet as possible within vessel operational constraints and safe working practices. Ideally the engines should be switched off. If the (idle) engine or auxiliary systems on the vessel are operational during measurements, the operator shall capture and report the SNR.

Drifting platforms can be considered an option for regions of very high current, to help reduce flow noise. In this case, a global positioning system (GPS) receiver on the drifting platform shall be used to provide a log of positional data. A synchronized time stamp on the audio-track is needed to accurately link to the GPS time.

Figure 2 shows examples of recommended bottom-anchored and surface-suspended mooring geometries. These mooring configurations agree with examples given in the NPL good practice guide (Robinson et al., 2014).

For this standard, a driving factor is distance between the hydrophone and the source; as well as the horizontal and vertical angles to the receiver (Chapter 5). The bottom-anchored configuration is practical for shallow water depth relative to the source; and the surface-suspended mooring is practical for any water depth. It is important to note that for moorings with a long cable between hydrophone and buoy or anchor, the hydrophone position could be affected by current flow. Devices such as tilt sensors on longer moorings may be useful for measuring hydrophone position deviations.

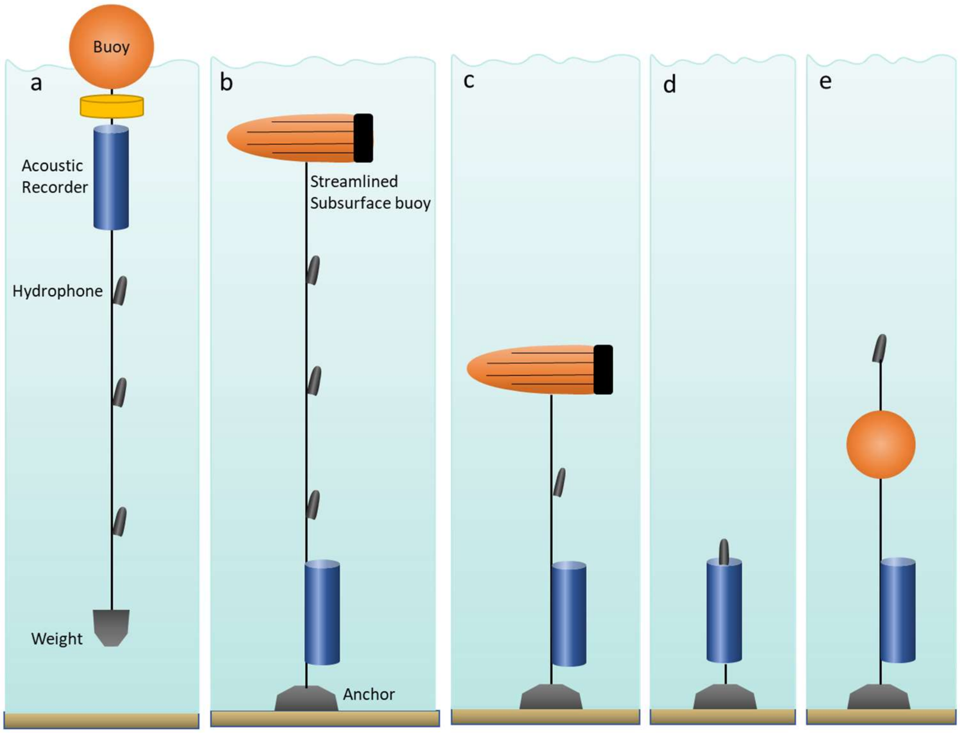

Figure 2 Example mooring configurations. (a) surface suspended hydrophone array for abeam aspect measurements; (b) bottom anchored array for abeam aspect measurements; (c) bottom anchored sensor for abeam aspect measurements in shallow water; (d) and (e) bottom anchored sensor for keel and endfire aspect measurements (see Chapter 5).

A third configuration is presented specifically for keel-aspect measurements (where the source travels over the measurement hydrophone). The keel-aspect mooring is without a buoy above the hydrophone to negate buoy (air) interference with the signal at the hydrophones.

4.1 Sensor deployment checklist

Follow the NPL Good Practice Guide (Robinson et al., 2014).

- Bottom-anchored moorings preferred:
  - Practical for shallow water depth relative to the source.
- Surface-suspended moorings:
  - Practical for any water depth.
- Hydrophone position could be affected by current flow, so use of mooring positioning equipment such as tilt and depth sensors are recommended.
- Water flow noise on hydrophones should be minimized using acoustically-transparent flow shields.
- Hydrophone mounts should be designed to isolate mooring vibrations from the hydrophones.
- The keel-aspect mooring should not have a buoy above the hydrophone.
- Vessel-based deployments:
  - Steps should be taken to minimize supporting vessel noise,
  - Ideally engines are off; if not, capture and report SNR.
- Drifting platforms can be considered for high current areas.
- GPS required on drifting platform.
- Require a synchronized time stamp on the audio-track.

5 Measurement procedures

This section describes standardized procedures for measuring underwater sound radiated by three classifications of sound sources (types A, B and C) within the operational area of oil and gas activities. The measurements are intended to introduce limited hindrance on operations. The measurements focus on obtaining data for quantifying the source output so that it can be used as input for modeling and assessment of its impact on marine life.

5.1 General considerations on preparations for the measurements

Because of the variety of sources, operational circumstances and limitations, and specific project requirements, the application of this standard requires preparation. Information needs to be gathered on the source to be measured, including its operational settings and the operational environment and conditions in which the measurements are to be performed.

The required information is elaborated in the following subsections. The details of the measurement plan will have to be determined based on this information.

5.1.1 Description of the source and its operational settings

The following questions need to be answered.

- Under which of the three source types (A, B, and C, as described in § 2.1) can the sound source to be measured be categorized? This standard does not apply to sources outside these three categories.
  For type C sources (production facilities):
  - Which activities are of interest?
  - Which facility components and operations are to be included in the source characterization?
- What are the main geometrical dimensions of the source?
  - What are the dimensions of the smallest closed surface (cylinder or other appropriate simple geometrical shape) that spatially bounds the source?
  - What are the three-dimensional coordinates of the assumed acoustic center, relative to the geometry of the actual source?
- What information is available on the underwater sound radiated by the source?
- What is the frequency range of the source?
- Can its radiated sound signals be classified as ‘pulse’, ‘nonpulse’ or ‘continuous’ (as described in § 2.2)?
- At which locations and over which time durations will the source be operated?
- At which settings will the source be operated and to what extent can its operation be adapted for the measurements?
  - Source types A and B are controlled by an operator; thus, the vessel may have the possibility to adapt its route and timing to optimize the measurements.
  - Source type C produce underwater sound as an unintended by-product of their activities, which may or may not be controlled by an operator, generally fixing the location and operation time.

5.1.2 Description of the operational environment and conditions

- At what location can the measurements be performed?
- What is the local water depth?
  - How does it vary over the operational area?
  - How is it affected by tidal variations?
- What information is available on the local sea water?
  - Acoustic models require local sound speed, as a function of depth, and absorption.
- What are the local sea floor features (are there rock outcrops or local channels)?
  - Generally, it is best to place measurement systems at locations where depth and seabed features are least variable.
- What information is available on the local sea floor composition?
  - Acoustic models require local sediment properties in terms of density, compressional (and shear) wave speed and absorption, as a function of sediment depth, (i.e., geoacoustic profile).
- What information is available on the local weather conditions?
  - Acoustic propagation is affected by wind generated surface waves,
  - Weather conditions may lead to practical limitations for measurements (safety and positional stability of measurement equipment).
- What information is available on other activities in and surrounding the operational environment?
  - Is it likely that the measurements are disturbed by operation of other sources in the project area or by nearby vessel traffic?

5.1.3 Specification of the requirements for source characterization:

- Which operational conditions are of interest for the measurements?
  - The operational conditions need to be sufficiently representative in measurements to address environmental impact assessment.
- Which frequencies are of interest for the source measurements?
  - The selection of the measurement frequency range needs to match with the frequency range of interest for environmental impact assessment.
- Which source metrics are of interest?
  - Source metrics depend on the class of signals (‘pulse’, ‘nonpulse’ or ‘continuous’, as described in § 2.2),
  - Source metrics depend on the metrics of interest for environmental impact assessment.
  - Local regulators may require specific metrics.
- What are the uncertainty requirements for the reported metrics?
- Which are the aspect and elevation angles at which the source characteristics are to be measured?

5.2 General considerations on frequency range

Since the aim of this standard is to provide measurement procedures for characterizing sources for use in environmental impact assessments, the frequency range of interest is driven by the sensitivity of marine life. The known hearing range of aquatic animals ranges from around 10 Hz up to roughly 200 kHz (Deng et al., 2014; Ketten, 1998; Mann et al., 2001; Mooney et al., 2012).

Note type B sources that operate at primary frequencies above 200 kHz, may also radiate lower frequency sound within the hearing range of marine life, below 200 kHz (Deng et al., 2014).

This standard advises a **frequency range** for characterizing sources that at least includes the **10 Hz to 50 kHz decidecade bands** (ranging from 8.91 Hz to 56.2 kHz). This requires a minimum sample rate above 113 kHz, which is practically achievable, because many off-the-shelf audio-recorders offer a 128 kHz sample rate.

Where possible, the acoustic frequency range should be extended up to the 160 kHz decidecade band (i.e., up to 178 kHz, which requires a minimum sample rate above 356 kHz), to cover the hearing range of high frequency marine fauna, such as the harbor porpoise.

In some cases, the project may be required to focus on specific frequency ranges that are relevant for local marine species. In these cases, this standard suggests, where possible, to measure, analyze and report the acoustic signals in the above-mentioned minimum frequency range as well, to enable comparability with the results of other studies.

5.2.1 *Frequency range checklist*

Minimum acoustic frequency range includes the 10 Hz to 50 kHz decidecade bands (with frequency range from 8.91 Hz to 56.2 kHz),

- requires a minimum sample rate of 113 kHz.

Where possible, extend the upper acoustic frequency range to include the 160 kHz decidecade band (i.e., up to 178 kHz),

- requires a minimum sample rate of 356 kHz.

5.3 General considerations on measurement geometry

The measurement procedures focus on characterizing the source sound emissions rather than the effect of the operating environment on the received sound levels. For spatially-distributed sources, the goal is to measure far field (see § 5.3.3) source emissions. Therefore, the measurement distances shall be far enough from the sources that near-field effects are negligible, but also near enough to avoid poor signal to noise ratio (SNR) in the measurements and uncertainties associated with quantifying long-range propagation effects. A specific difficulty in dealing with long-duration signals is that source position of moving sources at the time of sound signal emission becomes difficult to define. Nevertheless, if the source-receiver geometry variation is small over the signal repetition period, longer-duration signals can also be accommodated under the measurement procedures specified.

Figure 3 schematically illustrates the detailed measurement geometry and partners with Table to define the geometric parameters. Where possible, these procedures are aimed at determining source characteristics in terms of an appropriate source level, which requires that the source being measured qualifies as if it is an omnidirectional monopole point source. Deviations from this assumption are addressed.

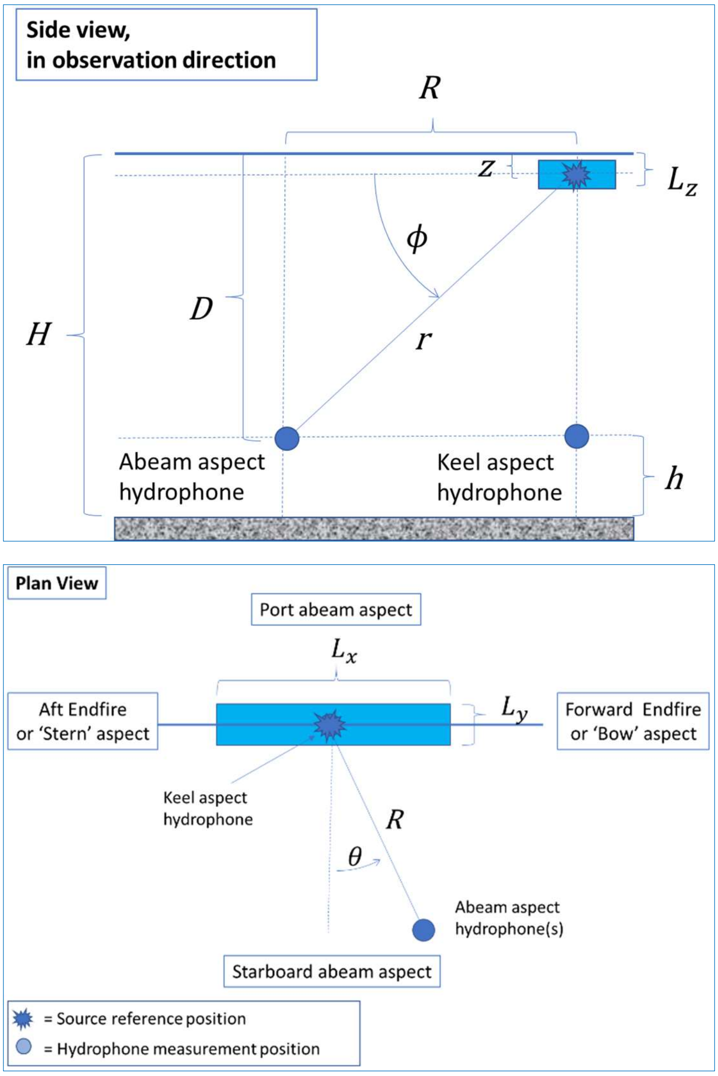

Figure 3 Schematic side view (top) indicating source traveling toward the reader, and plan view (bottom) of the measurement geometry indicating source traveling left to right. The sound source is contained within a (blue) bounding box (with length L_x, width L_y and height L_z). Far field sound emission characteristics are determined for a hypothetical point source inside the box, which is assumed to be at a distance z below the water surface. The figure parameters are defined in Table .

Table 2 Defined geometric parameters for Figure 3 and in text.

Symbol	Description
L_x	horizontal source dimension (length)
L_y	horizontal source dimension (width)
L_z	vertical source dimension
z	source depth ($z \leq L_z$)
H	water depth
r	slant range (hydrophone distance)
ϕ	vertical observation angle
θ	horizontal (azimuthal) observation angle
h	hydrophone minimum height above sea floor
$R = r\cos\phi$	horizontal hydrophone distance (far field)
$D = z + r\sin\phi$	hydrophone depth ($D \leq H - h$)
$A = \max(L_x, L_y, L_z)$	maximum source dimension

5.3.1 *Vertical and horizontal observation angles*

Measuring the full directionality of source emissions is impractical and beyond the scope of the proposed measurement procedures. Instead, five main observation directions are defined, one keel and four horizontal aspects (see the plan view in Figure 3):

- 'Keel aspect' addresses the sound emission nominally in the vertical direction ($\phi = 90°$), directly below the source[2]. This direction is of particular interest for type A and B sound sources because animals situated directly beneath a source will often experience the highest sound levels.

The four main horizontal aspects (bow, stern, and port and starboard abeam) are defined to characterize sound emissions mainly in horizontal directions. These measurement geometries also prescribe associated vertical angles, but the goal is to characterize sound emissions that mainly propagate horizontally to assess the exposure of animals at larger distances from the source. The bow is in front of the source and aft is behind the source. Looking to the bow, port is to the left and starboard is to the right of the source, both 'abeam' aspects (port and starboard) are perpendicular to the source track. For ships, abeam aspect is the direction in which the radiated noise level measurements of ships are made, according to the ISO 17208-1 standard. For the type A and B sources, the abeam definition is adapted to indicate the bearing projected at right-angles from the bow and aft line, outwards from the center of the source. For type C sources, the horizontal directionality needs to be specified case-by-case.

This standard requires measurements from different aspects:

- For type A sources the standard requires measurements from at least three aspects: either the bow or stern aspect, either the port or starboard abeam aspect, and the keel aspect.
- For type B sources the standard requires measurements from at least two aspects: either the port or starboard abeam aspect, and the keel aspect.
- For type C sources the user should define the aspects.

The vertical observation angle (ϕ), see Figure 3, needs to be representative of sound emission angles that lead to long-range propagation. Those propagation paths are relatively shallow, but to obtain reliable measurements it is necessary to maintain a minimum ϕ to avoid excessive surface interference effects that occur at very shallow angles. Therefore, for this standard the following three abeam measurement angles were selected: $\phi = 15°$, $30°$ and $45°$, which are based on ISO 17208-1 geometry specified for radiated noise level measurements of ships.

The opportunity to measure the horizontal aspect source emissions at these three angles is limited by four primary factors:

1. the water depth (H), see § 5.3.4;
2. the distance between the hydrophone and the sea floor (h), see § 5.3.5;
3. the source depth (z);
4. the minimum measurement distance (R) necessary to be in the acoustic far field of the source (see § 5.3.3).

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[2] Measuring in keel aspect may not always be possible due to operational constraints.

5.3.2 *Source dimensions*

This standard addresses a broad range of source shapes and sizes, therefore a brief description of how to determine the source dimension is provided.

For this standard, as illustrated in the Figure 3 geometry, it is assumed that the sound source is contained within a bounding box with length L_x, width L_y and height L_z. Far field sound emission characteristics are determined for a hypothetical point source inside the box, which is assumed to be at a distance z below the water surface.

5.3.3 *Measurement distance*

Ideally, source characterization measurements are made with sensors in the far field of the source, so that it can be described as a point source (see § 2.3). There are multiple definitions of far field, acoustic, geometric, and hydrodynamic (see Appendix A, Table A.3).

As a first requirement (from ANSI/ASA S1.20:2012 developed by the Acoustical Society of America (ASA) and accredited by the American National Standards Institute (ANSI)), the minimum range r that is required for measuring in the far field, should fulfill:

$$r > \pi A^2/4\lambda \qquad \text{Equation 5}$$

with acoustic wavelength $\lambda = c/f$ (for sound speed c and frequency f) and A the maximum source dimension (§ 5.3.2), defined as:

$$A = \max(L_x, L_y, L_z) \qquad \text{Equation 6}$$

As a second requirement r should be large compared with the source dimension. ANSI/ASA S1.20:2012 requires $r > 0.5A$ and IEC 60565:2007 requires $r > 5A$. Our own analysis finds that difference in pressure relative to that of a point source at distance r is less than 10 % when $r > A$. This difference corresponds with a decibel error less than 1 dB. Common source dimensions for type A and B sources are small relative to the minimum fixed measurement distances specified in this standard, and it is unlikely that measurements would be performed at distances less than A. Consequently, the requirement that $r > A$ will rarely be a limitation. An illustration for type A sources is provided in § 5.6.1.

The above requirement for the acoustic far field does not necessarily apply to type C sources, that may contain multiple incoherent source mechanisms. The maximum dimensions associated with these source mechanisms are generally smaller than the maximum dimensions of the complete platform and unknown at the time when the measurement locations are planned. Hence, the frequency dependent minimum range for measuring in the far field (Equation 1) is not required for type C sources (see § 5.7).

Though the minimum far-field distance requirement formally applies to the 'slant range' r in the direction of the vertical observation angle, we recommend selecting a horizontal measurement range R greater than this minimum distance. Moreover, the first criterion ($r > \pi A^2/4\lambda$) results in a minimum range that linearly increases with frequency. Hence, in practice the calculation of a minimum measurement distance requires a selection of a maximum frequency (corresponding with a minimum wavelength) of interest. Note that the above formulas are derived for radiated signals that are coherent over the maximum dimensions of the source. For many sources the coherence is reduced at higher frequency. Practical minimum far-field observation ranges per source type are provided in § 5.6 and § 5.7.

It is worth mentioning that there is an additional definition for the hydrodynamic far field (Appendix A, Table A.3) of a sound source (Morse and Ingard, 1986) which requires that the radiated sound pressure and sound particle velocity are in phase. The corresponding near field typically occurs at distances (r) smaller than an acoustic wavelength $(\lambda = 2\pi/k)$, where $kr \ll 1$. For a simple monopole point source, the sound particle velocity has a large component out of phase with the sound pressure in the hydrodynamic near field. However, this will not affect pressure measurements in the hydrodynamic near field. The near field of a dipole sound source (such as a point source close to the water surface) is more complicated, but also more concentrated near the source. Hence this hydrodynamic near field is ignored for the purpose of these source measurement procedures.

5.3.4 *Shallow and deep water*

This standard defines minimum water depths for both the deep water (§ 5.6.2) and shallow water (§ 5.6.3) measurement geometries. These depths are defined by the source depth, minimum far-field measurement distance, and vertical observation angle requirements.

5.3.5 *Requirements for hydrophone location*

Minimum distance between hydrophone and source
In addition to the requirement to measure in the acoustic far field, there may be external requirements to maintain a safe minimum distance between source and hydrophone. For example, for the safety of personnel and equipment, or for the practicality associated with deploying and retrieving moorings near production activities.

Minimum height above sea floor
This standard does not prescribe a minimum height above sea floor. There is no general standard for selecting a minimum height of the hydrophone above the sea floor[3]. Proximity of the hydrophone to the sea floor may affect the measurements due to contributions of bottom-reflected sound, interface waves (e.g., Scholte), and other sea floor vibrations that can cause hydrophone accelerations leading to unwanted noise. Alternatively, flow noise on hydrophones close to the sea floor can be reduced because water currents there are often lower. Hence, the effects of hydrophone position relative to the sea floor will need to be evaluated for each project to ensure they are accounted for appropriately. The approach is to calculate an omni-directional source level SL for type A sources, or a SL in a given direction for type B sources, by correcting the measured SPL with propagation loss that accounts for the seabed reflection if necessary (see Chapter 7).

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[3] The ISO 18406 standard for measuring the sound from marine piling requires a minimum distance of 2 m above the sediment. The U.S. Bureau of Ocean Energy Management (requirements for sound source verification) recommends measurements from at least three reference distances at two depths: (1) at mid-water and (2) approximately 1 m above the sea floor.

5.4 Requirements for statistical analysis of source output

Multiple measurements over time are required to evaluate statistical variations caused by:

- variations of the source signal (a sensor at a fixed distance from a type C source can be useful to provide information on source signal variations over time);
- geometry variations (for type A and B sources that are generally towed or mounted on a moving platform), including variations due to small-scale seabed features and geoacoustic parameter differences that affect seabed reflectivity;
- variations in environmental conditions (wind, currents, etc.).

Multiple sensors are required to evaluate statistical variations caused by:

- evaluating the source metrics in different aspects and frequency bands;
- statistical uncertainties in propagation loss estimation.

5.5 General considerations on measurement environment and conditions

Hydrophone locations shall be selected such that no objects block a line-of-sight from the hydrophone to the full surface that encloses the source or affect the sound pressure measurements via acoustic reflections.

Hydrophone locations shall be selected such that the water depth along the trajectory between source and hydrophone is close to uniform or varies with a gradual slope.

The environmental conditions (weather, other activities) shall not change during the selected measurement periods.

The environmental conditions should be such that effects of wind and waves on background noise and sound propagation do not adversely affect the measurements.

Avoidance of disturbance by other noise sources (e.g., ships). Steps should be taken to minimize supporting vessel noise. Deployments undertaken from a vessel shall be made under conditions as quiet as possible within vessel operational constraints and safe working practices. Ideally the engines should be switched off. The operator shall capture and report the SNR.

Hydrophone moorings should isolate the transducers from motion caused by sea-surface waves and from water currents.

5.6 Procedure for measuring type A and B sources (geophysical exploration surveys)

Measurement geometries and procedures for type A and B sources are similar. Both source types are operated from a moving platform, such as a tow-vessel, both result in multiple repeated signals, and both can be controlled by an operator.

The measurement procedures for type A and B sources are intended to characterize far-field source levels in the port and starboard abeam aspects, bow and aft endfire aspects, and keel aspect (§ 5.3.1). Deep water and shallow water procedures are defined for the three primary aspects, leading to six separate measurement geometries: deep abeam, deep endfire, deep keel, shallow abeam, shallow endfire, shallow keel.

Figure 3 top, shows the side view perspective of the measurement approach and bottom shows the plan view perspective. For both deep and shallow water conditions, the source transits along a track (i.e., source track) through a measurement zone that lies atop a keel aspect hydrophone, and perpendicular to the abeam aspect hydrophone(s). The source should transit inside the measurement zone and as close as possible to its axis. The axis (i.e., source transit) of the measurement zone is perpendicular to the horizontal distance R of the abeam aspect hydrophone(s), where R is the horizontal offset distance for abeam measurements (§ 5.2.1).

The source position at the time of each impulse shall be recorded accurately as it passes through the measurement zone. The length of the measurement zone is $X = 2R\tan 30°$. The measurement zone is centered on the source track and is given a width of $Y = R/5$ to accommodate up to ± 10 % range deviation, that might result from the source being towed slightly off-track. This allowance is expected to result in maximum measurement errors less than 1 dB. However, when measuring Type B sources with narrow cross-track beamwidths, the off-track deviation may have to be smaller to ensure the keel hydrophone samples the beam. For the same reasons, source location uncertainty should be less than $R/20$ in the directions both parallel to and perpendicular to the measurement zone axis.

5.6.1 *Horizontal offset distance for abeam aspect measurements*

Abeam aspect measurements are performed by deploying either three hydrophones (for a deep-water case) or one hydrophone (for a shallow water case) perpendicular to the source track. This standard recommends a minimum distance approach to provide consistency between project measurements and allows for positional uncertainties relative to shorter offsets. The smallest horizontal offset R from the source track to the abeam hydrophones is defined as the larger of 100 m and the acoustic far-field distance.

This minimum specified distance depends on source type. For type A we recommend 100 m and for type B we recommend 50 m. For type A sources, a practical upper limit for the frequency range that determines the acoustic far-field distance (§ 5.3.3) is about 1.5 kHz (λ = 1 m). Thus, the minimum measurement distance for a type A source with maximum length A is $R = \frac{\pi A^2}{4\ \mathrm{m}}$. This far-field distance is based on an acoustic wavelength of 1 m. The minimum distance of 100 m also allows for the type A measurement zone to be of sufficient size to accommodate the low signal repetition rate, which is not necessary for type B sources. This minimum distance is illustrated for a range of maximum source dimensions in Figure 4.

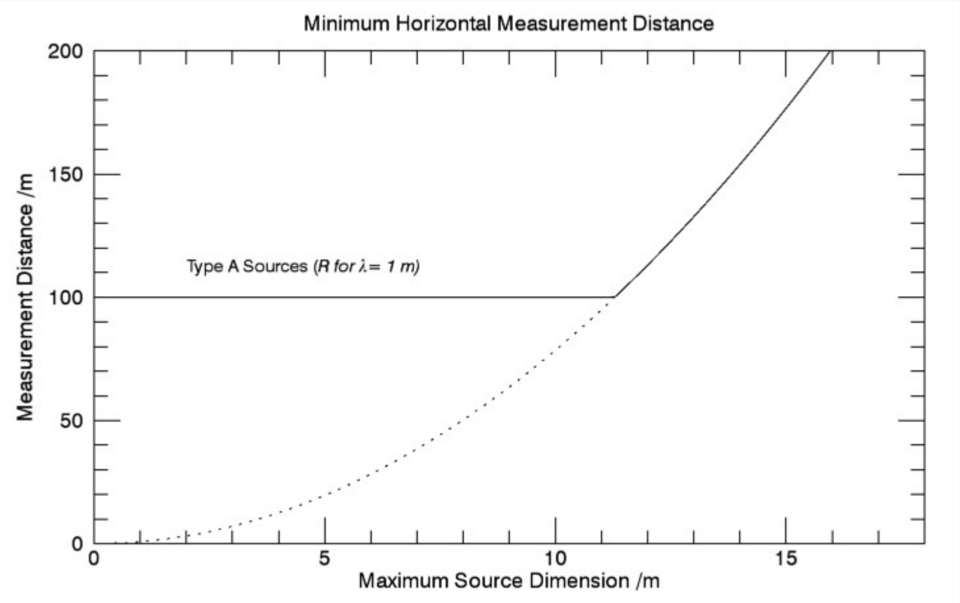

Figure 4 Minimum horizontal measurement distance for type A sources versus maximum source dimension.

A maximum value for R is not defined, but in practice it will be limited by the need to maintain sufficient SNR as discussed in § 5.6.12.

For type B sources, the smallest wavelength will depend on the highest important frequency of the signal being measured. The minimum far-field distance will consequently depend on the source's highest acoustic frequency. The minimum horizontal measurement distance, R, for type B sources is the greater of 50 m and the far-field distance, as shown in Figure 5.

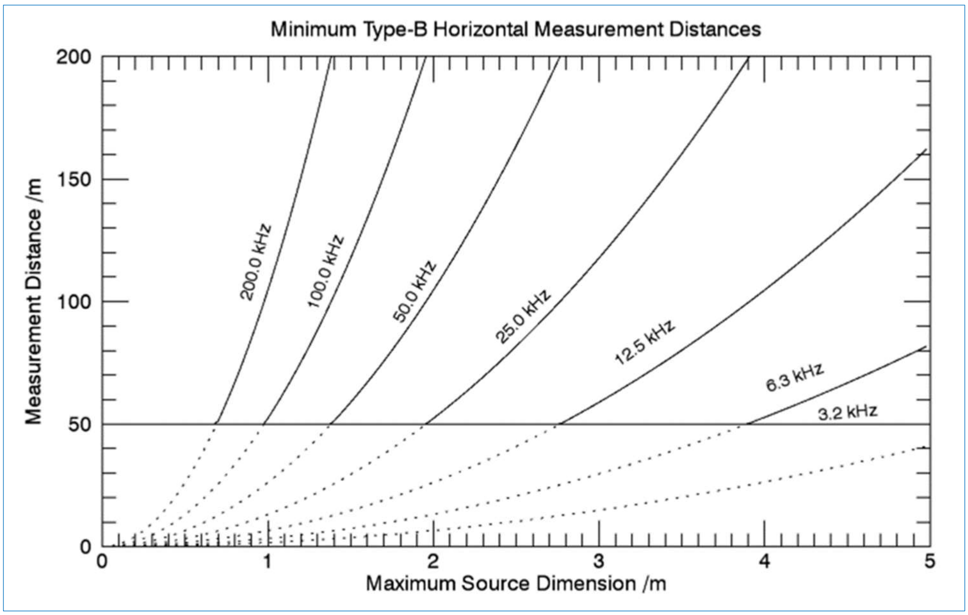

Figure 5 Minimum horizontal measurement distances for type B sources for 7 example upper source frequencies, versus maximum source dimension.

5.6.2 *Minimum water depth for deep geometry*

The minimum water depth allowed for deep geometry is required to obtain measurements of at least $\phi = 45°$ vertical angle (ref Figure 3) when the source reaches its closest point of approach (CPA), corresponding with horizontal distance R, to the abeam hydrophones. This requires that the water depth be at least the source depth plus R.

The minimum horizontal far-field observation distance R and the maximum vertical observation angle ($\phi = 45°$), as illustrated in the Figure 3 geometry, define the minimum water depth that is required for the deep-water geometry measurements. The water is too shallow for measuring at the largest vertical observation angle when:

$$H \leq h + z + R \qquad \text{Equation 7}$$

For abeam measurements at the maximum vertical observation angle ($45°$) this means that the water is too shallow when the water depth is less than the horizontal measurement distance R plus the source depth (z), plus the distance of the hydrophone above the sea floor (h).

5.6.3 *Minimum water depth for shallow geometry*

The minimum water depth allowed for shallow geometry is defined to obtain measurements of at least $\phi = 15°$ vertical angle (ref Figure 3) when the source reaches its CPA, corresponding with horizontal distance R, to the abeam hydrophones. This requires that the water depth be at least the source depth plus $R \tan 15°$ (approximately source depth plus 0.268 R).

5.6.4 *Abeam aspect measurements in deep water*

The hydrophone geometry for abeam measurements in deep water uses three hydrophones positioned at horizontal distance R from the source track and with depths set to sample the direct-path sound emissions at angles $\phi = 15°, 30°, \text{and } 45°$ when the source is at CPA, as shown in Figure 6.

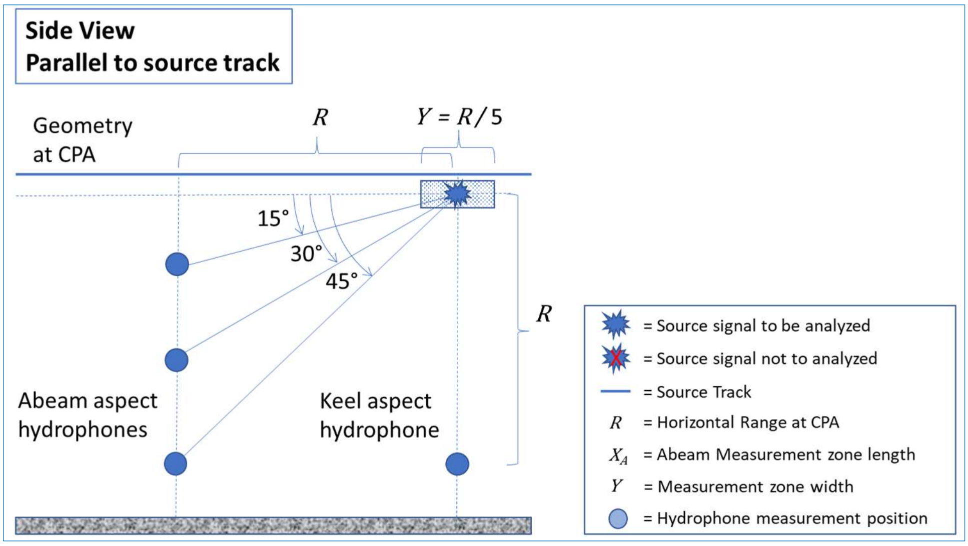

Figure 6 Side view of deep abeam and keel measurement geometry. The allowed off-track deviation will have to be reduced for type B sources with narrow cross-track beam widths to ensure the keel hydrophone samples the beam.

A measurement zone is defined along the portion of the track subtending an angle of ±30° relative to line segment between the abeam hydrophone position and the source's CPA position, as shown in Figure 7. The measurement zone is centered on the source track and is given a width of $Y = R/5$ to accommodate up to ±10 % range deviation, that might result from the source being towed slightly off-track. This allowance is expected to result in maximum measurement errors less than 1 dB. However, when measuring type B sources with narrow cross-track beam widths, the off-track deviation may have to be smaller to ensure the keel hydrophone samples the beam.

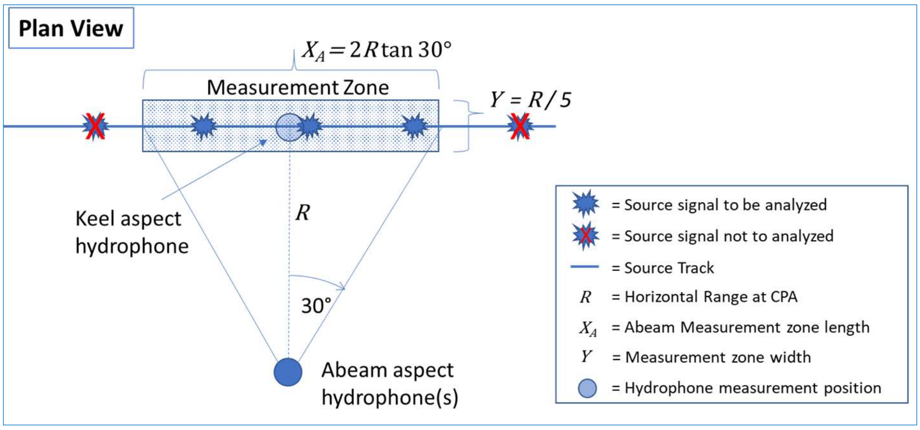

Figure 7 Plan view of abeam and keel aspect measurement zone relative to hydrophone locations.

5.6.5 *Keel aspect measurements in deep water*

The keel aspect hydrophone in deep water is positioned directly under the source track at depth R below the source depth as illustrated in Figure 6. Therefore, the keel aspect hydrophone depth below surface is $D = z + R$. A source measurement zone for keel aspect measurements in deep water is defined such that the angle subtended by the source at the hydrophone position is less than $30°$ from vertical, as illustrated in Figure 8. If the same value for R is used to define the abeam horizontal offset and keel measurement hydrophone depth below source in deep water, then the abeam and keel measurement zones will coincide.

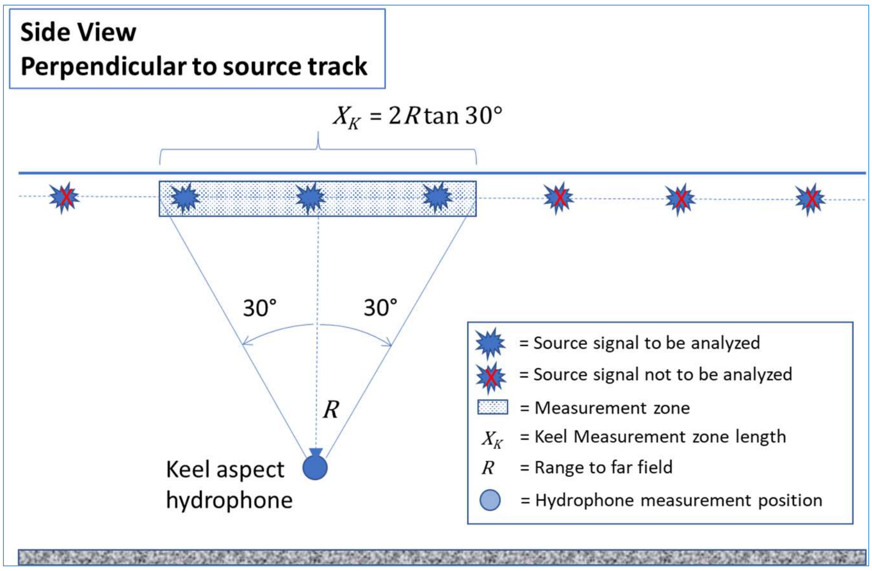

Figure 8 Side view of keel aspect geometry for deep water.

5.6.6 *Endfire aspect measurements in deep water*

The endfire aspect measurements can be performed on the same hydrophone used for keel aspect measurements, but the endfire measurements are made at distance from the hydrophone rather than directly overhead. The endfire measurements zone is defined along the source track such that the direct path propagation angles lie between $15°$ and $45°$ from horizontal, as illustrated in Figure 9. The length of the endfire aspect measurement zone is approximately 2.73 R, as shown in Figure 9 and Figure 10.

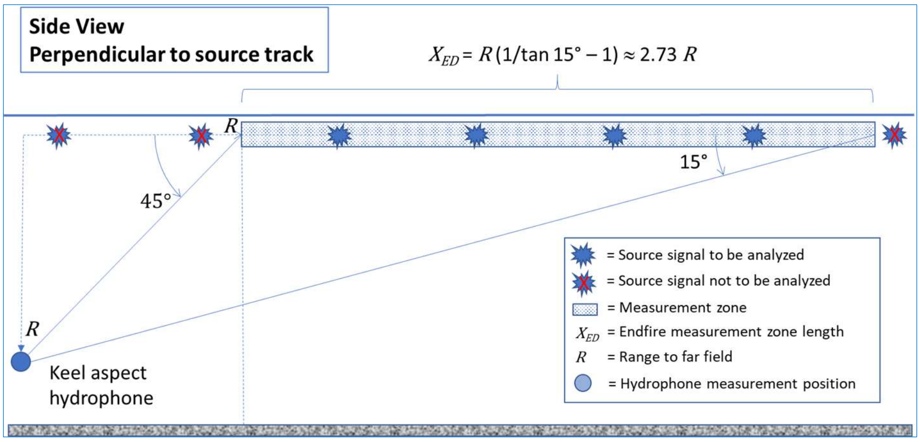

Figure 9 Side view of endfire aspect geometry for deep water.

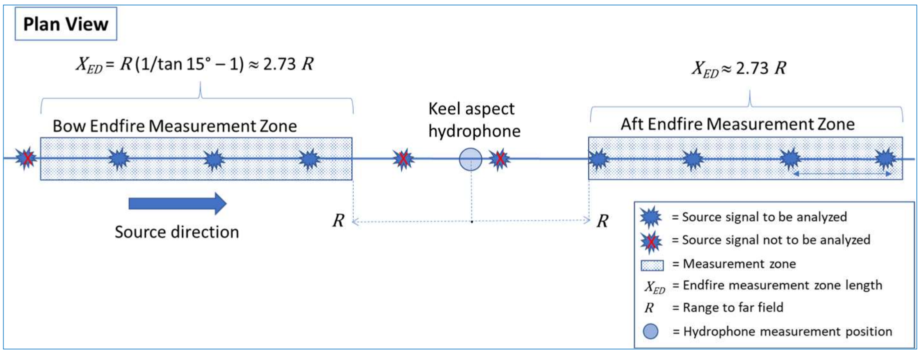

Figure 10 Plan view of endfire aspect geometry for deep water.

5.6.7 *Abeam aspect measurements in shallow water*

The hydrophone geometry for abeam aspect measurements in shallow water uses a single hydrophone positioned at horizontal distance R off the source track and at depth as close as possible to the seabed to maximize the angle ϕ of the direct acoustic path. This will result in direct path propagation angles between $15°$ and $45°$ from horizontal when the source is at CPA, depending on water depth. These limiting angles correspond respectively to the minimum and maximum possible shallow water depths: i.e., $z + R \tan 15°$ and $z + R$. The plan view for this geometry is the same as for the abeam aspect deep water measurement. Like the deep-water case, a measurement zone is defined by the portion of the source track that subtends the angular range $\pm 30°$ at the hydrophone, centered on the direction perpendicular to the source track as illustrated in Figure 7. Also like the deep-water case, the measurement zone width is $Y = R/5$ to allow for some deviation of the source position off the centerline of its planned tow track. The side view of the abeam aspect measurement geometry for shallow water is provided in Figure 11.

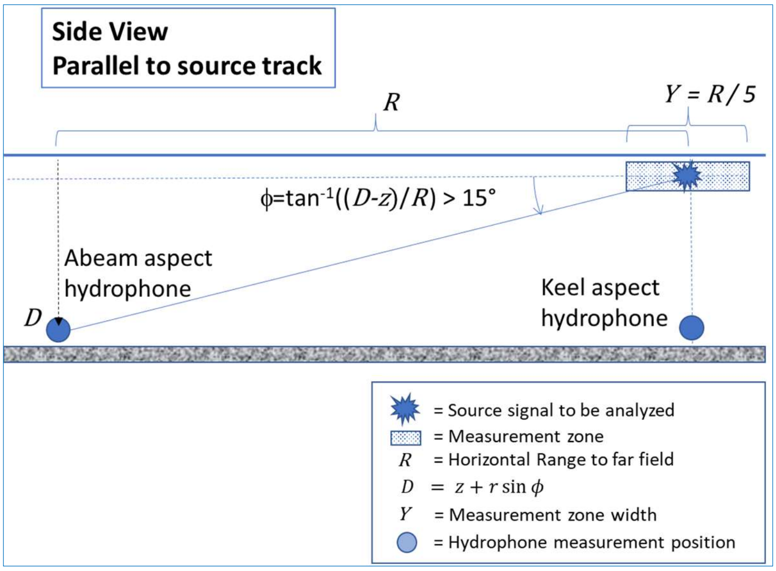

Figure 11 Side view of abeam aspect and keel aspect geometry for shallow water. The allowed off-track deviation will have to be reduced for type B sources with narrow cross-track beam widths to ensure the keel hydrophone samples the beam.

5.6.8 *Keel aspect measurements in shallow water*

The keel aspect hydrophone for shallow water measurements is placed as close as possible to the seabed as illustrated in Figure 11. The distance of this hydrophone from the source will be less than R and possibly less than the minimum acoustic far-field distance. Nevertheless, this measurement is important as in many cases it will characterize the maximum sound pressure experienced by near-seabed dwelling fauna. Importantly, and unlike the deep-water case, the length of the shallow water keel aspect measurement zone is less than that of the shallow water abeam aspect measurement zone. The allowed off-track deviation of $Y = R/5$ may have to be reduced for keel aspect measurements of type B sources with narrow cross-track beamwidth, to ensure the keel aspect hydrophone samples the beam.

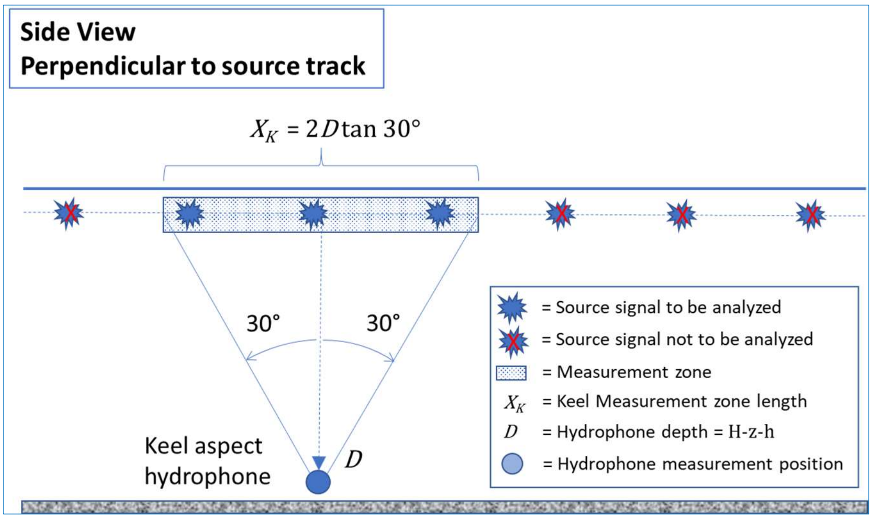

Figure 12 Side view of keel aspect measurement geometry.

5.6.9 *Endfire aspect measurements in shallow water*

The endfire aspect measurements in shallow water are made on the keel aspect hydrophone while the source approaches and departs from passing over the hydrophone. The bow endfire measurement is made on approach and aft endfire measurement made on departure. The bow endfire measurement zone is defined as the portion of source track starting when the vertical angle of the direct acoustic path to the hydrophone reaches $15°$ from the horizontal. It ends when the angle reaches its maximum value of $\tan^{-1}((D - z)/R)$, which is at most $45°$ and corresponds with the source is at horizontal distance R from overhead the hydrophone. This geometry is illustrated in Figure 13. The aft endfire measurement zone is defined similarly but mirrored on the departure side of the hydrophone so sound measurements are made from behind the source.

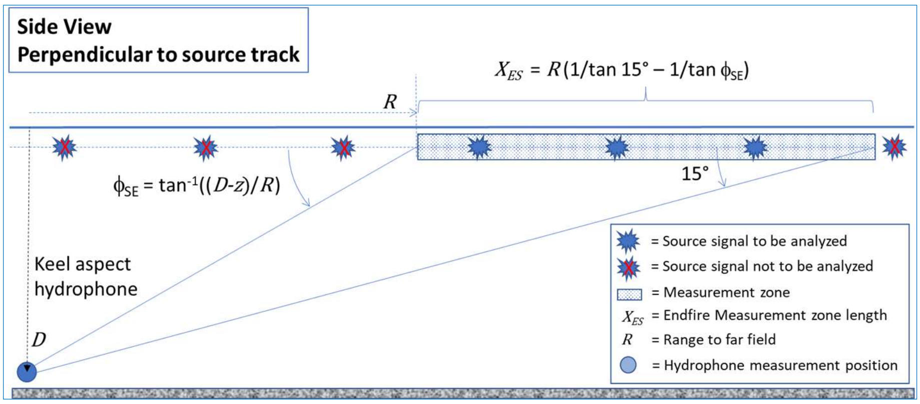

Figure 13 Side view of shallow endfire aspect measurement geometry.

5.6.10 *Number of pulse measurements required*

The number of impulses occurring within a measurement zone will depend on the impulse spacing along the path (Figure 7), which is a function of the tow speed and pulse rate. The standard requires at least five source pulses be sampled to allow for averaging of calculated metrics over multiple pulses. More than one pass may be required to obtain at least five impulses. More than one monitoring location can be used to achieve a greater number of samples per pass, although the measurement zones for each location should not overlap.

5.6.11 *Non pulse sources*

For sources with nonpulse signals (Table) with durations of more than a few seconds, source movement over the time period of a single sweep or signal repetition may lead to difficulty choosing a representative source-hydrophone distance for the sweep or signal. The source location at the half-duration time will be used as the location for propagation loss calculations in order to calculate source levels (Chapter 7). In all cases, the absolute deviation in source-hydrophone separation distance, over the duration of the signal, from the distance at half-duration time must be less than 10 % of the source-hydrophone separation distance at the half-duration time.

5.6.12 *Background noise measurement for type A and B sources*

- The (electronic) self-noise of the full measurement chain shall be measured prior to deployment. This is normally expressed as a noise-equivalent sound pressure spectral density level in dB re 1 μPa^2/Hz (IEC 60565, 2006, ANSI S1.20 2012). If the electrical impedance of the hydrophone is not appreciably affected by its acoustical load, this measurement can be made with the hydrophone suspended in air or vacuum in a soundproof chamber. The system self-noise varies with frequency and as a result is typically presented as a noise spectral density level versus frequency.

- The equivalent root-mean-square (rms) system noise sound pressure shall be recorded as close as possible in time to the source measurements. For these measurements, the source is required to be located at least ten times the CPA distance from the hydrophone to reduce its contribution to the measurement.
- The tow ship noise at the measurement location shall be recorded for at least one transit of the ship with the (A or B) source switched off and when the source is at the same CPA distance as during the source measurements.

5.6.13 Procedural type A and B measurement checklist

- ☐ Purpose of standard is to characterize the source sound emissions, not the effect of the operating environment on the received sound levels.
- ☐ Measure far-field source emissions.
- ☐ Avoid poor SNR in the measurements.
- ☐ Avoid uncertainties associated with quantifying long-range propagation effects.
- ☐ Source being measured qualifies as if it is an omnidirectional monopole point source.
- ☐ The opportunity to measure the horizontal aspect source emissions at these three angles is limited by four primary factors:
    - o water depth (H), see § 5.3.4,
    - o minimum distance between the hydrophone and the sea floor (h),
    - o the source depth (z),
    - o minimum measurement distance (R) to be in the acoustic far field.
- ☐ Calculate the source dimensions and the acoustic far-field distance based on source type and maximum source dimension and acoustic wavelength (see § 5.6.1).
- ☐ Ensure water depth at measurement site meets the minimum value for the deep or shallow geometry chosen, as discussed in § 5.3.4.
- ☐ Ensure hydrophone is positioned to meet the minimum observation distance while upholding personnel and equipment safety (§ 5.3.5).
- ☐ Unobstructed line-of sight between hydrophones and sources (§ 5.3.5).
- ☐ Uniform water depth between hydrophone and source,
    - o gradual slope is allowable when necessary.
- ☐ Consistent environmental conditions (weather, other activities) during measurements.
- ☐ Avoid and minimize other noise sources.
- ☐ Deployments undertaken from a vessel shall be made under conditions as quiet as possible accounting for safe working practices,
    - o should switch engines off,
    - o should capture and report the SNR.
- ☐ Type A and B source measurements are intended to characterize far-field source levels in different measurement aspects. Refer to Figure 3 for measurement approaches in the side view and plan view perspectives.
- ☐ Minimum number hydrophones required are:
    - o two for shallow waters,
    - o four for deep waters.

- ☐ The source transits along a source track, through a measurement zone as close as possible to its axis:
  - atop a keel aspect hydrophone,
  - perpendicular to the abeam aspect hydrophone(s),
  - The source position at the time of each impulse shall be recorded accurately as it passes through the measurement zone.
- ☐ Measurement zone:
  - length is $X = 2R \tan 30^\circ$,
  - width is $Y = R/5$ to accommodate navigational variance,
  - Source location uncertainty should be less than $R/20$ in the directions both parallel to and perpendicular to the measurement zone axis.
- ☐ The smallest horizontal offset R from the source track to the abeam hydrophones is defined as the larger of 50 or 100 m and the acoustic far-field distance. This minimum specified distance depends on source type.
  - Type A, recommended 100 m.
    - A practical upper limit for the frequency range that determines the acoustic far-field distance (§ 5.3.3) is about 1.5 kHz (λ = 1 m).
    - Thus, the minimum measurement distance for a type A source with maximum length A is $R = \frac{\pi A^2}{4\ \mathrm{m}}$ (Figure 4).
    - Maximum for R is not defined but will be limited by sufficient SNR (§ 5.6.12).
  - Type B recommended 50 m.
    - The smallest wavelength will depend on the highest important frequency of the signal being measured.
    - The minimum far-field distance will consequently depend on the source's highest acoustic frequency.
    - The minimum horizontal measurement distance, R, is for the greater of 50 m and the far-field distance (Figure 5).

5.7 Procedure for measuring type C sources (production activities)

5.7.1 Scope

The procedure is applicable to static facilities (mounted or moored platforms) for oil and gas production activities, containing an unspecified number of sound sources. Vessel activities near the platforms and also dynamic positioning activities of floating platforms are included. The combination of all included activities is treated as a single source. The procedure is based on the assumption that time periods can be defined over which the facility operates in a representative steady condition for which the radiated sound characteristics are reported. If there is an interest in the underwater sound production when the facility operates at different conditions, then the measurements shall sample the range of variations.

5.7.2 Measurement geometry

Two different source configurations are considered here:

1 floating platforms in deep water (Figure 3, top);
2 bottom mounted platforms that extend over the water depth (Figure 14).

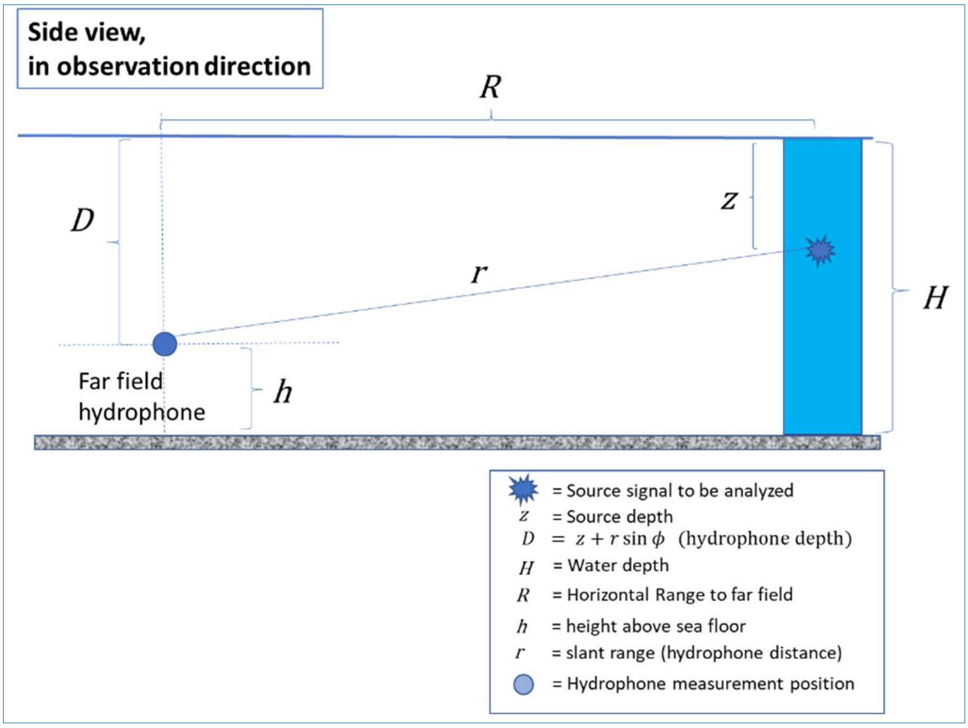

Figure 14 Type C measurement geometry for bottom mounted platforms (side view).

- Hydrophones shall be deployed at a horizontal distance greater than or equal to 1.5 times the maximum horizontal dimension of the surface that encloses the source, measured from the position on the contour that is closest to the hydrophone.
- If the water depth surrounding the source is smaller than the horizontal measurement distance, the measuring hydrophone shall be positioned in the lower half of the water column, between a height 1 m above the sea floor and one-half the total water depth.
- If the water depth is greater than the horizontal measurement distance and the source is floating (Figure 3), the hydrophone depth shall either be determined on the basis of the horizontal measurement distance from the geometric center of the source, to achieve a 15, 30, and 45-degree vertical observation angles.
- One reference hydrophone shall be deployed at a representative position during the full measurement period, to monitor the effect of time variations of the sound radiation.
- Additional hydrophone deployments are required to monitor spatial variations of the sound radiation. These may be either moored or vessel-based systems.
- The number of measurement locations depends on the requirements for the number of aspect angles for which the source needs to be characterized as well as on the uncertainty requirements, since additional data (e.g., at multiple distances along the same radial direction out from the source) can contribute to reducing the uncertainty.
- A vertical array of hydrophones at multiple depths can also contribute to reducing the uncertainty.

5.7.3 Background noise measurements for type C sources

- The (electronic) self-noise of the full measurement chain shall be measured prior to deployment. This is normally expressed as a noise-equivalent sound pressure spectral density level in dB re 1 μPa^2/Hz (IEC 60565, 2006, ANSI S1.20 2012). If the electrical impedance of the hydrophone is not appreciably affected by its acoustical load, this measurement can be made with the hydrophone suspended in air or vacuum in a soundproof chamber. The system self-noise varies with frequency and as a result is typically presented as a noise spectral density level versus frequency.

- Where possible, background noise shall be recorded as close as possible in time to the source measurements. This can only be done for type C sources with a specified operation time (e.g., drilling).
- For sources that are continuously operational, background noise at the sensor location cannot be measured. Care needs to be taken in the design of the deployment systems to avoid contamination from parasitic signals due to the deployment method for the hydrophone and recording system and its interaction with the surrounding environment (e.g., flow noise, surface heave, cable strum and mechanical noise).

5.7.4 Procedural type C measurement checklist

- ☐ Purpose of standard is to characterize the source sound emissions, not the effect of the operating environment on the received sound levels.
- ☐ Measure far-field source emissions.
- ☐ Avoid poor SNR in the measurements.
- ☐ Avoid uncertainties associated with quantifying long-range propagation effects.
- ☐ For type C sources, the horizontal directionality needs to be specified case-by-case.
- ☐ Calculate the source dimensions and the acoustic far-field distance based on source type and maximum source dimension and acoustic wavelength (see § 5.6.1).
- ☐ Ensure water depth at measurement site meets the minimum value for the deep or shallow geometry chosen, as discussed in § 5.3.4.
- ☐ Ensure hydrophone is positioned to meet the minimum observation distance while upholding personnel and equipment safety (§ 5.3.5).
- ☐ Unobstructed line-of sight between hydrophones and sources (§ 5.3.5).
- ☐ Uniform water depth between hydrophone and source,
  - o gradual slope is allowable when necessary.
- ☐ Consistent environmental conditions (weather, other activities) during measurements.
- ☐ Avoid and minimize other noise sources.
- ☐ Deployments undertaken from a vessel shall be made under conditions as quiet as possible accounting for safe working practices:
  - o should switch engines off,
  - o should capture and report the SNR.

5.8 Required auxiliary measurements

5.8.1 Water depth

The water depth at the measurement location shall be known. If the opportunity is available, make the measurement.

5.8.2 Distance

The distance from the geometric center of the source to the measurement location shall be determined with an accuracy of 5 % or better.

NOTE: The range can be determined using laser range finding equipment at relatively short ranges. For greater ranges, a more practical solution is to use the GPS coordinates of the source and measurement position to derive the range.

5.8.3 Sound speed and absorption

The underwater sound speed and absorption profiles in the measurement area shall be recorded at the start of the measurement period and should be repeated at subsequent measurement days.

NOTE: The sound speed and absorption profiles can be obtained from measurements of conductivity, temperature, and hydrostatic pressure as a function of depth in the water column using a conductivity, temperature, and depth (CTD) probe. From this information the sound speed and absorption profiles can be calculated from standard equations, e.g., (Mackenzie, 1981; van Moll et al., 2009; Ainslie and McColm 1998, Francois and Garrison, 1982a,b; Ainslie, 2010 § 2.1.1.3).

5.8.4 Wind speed

The wind speed at a specified location and at a height of 10 m above the sea surface, averaged over 10 minutes shall be recorded before the start of the measurements and after completion.

6 Data processing (received sound metrics)

6.1 Introduction

The term "data processing" is used here to mean the conversion from recorded sound signals to processed metrics of received sound at the position of each hydrophone such as SPL or sound exposure level (SEL), see the Phase 1 Processing standard (Ainslie, Prior, & de Jong, E&P sound and Marine Life JIP Standard: Underwater Acoustics - Task 2: Processing, 2018). Procedures for converting these to source output metrics are described in Chapter 7.

The focus is on metrics for describing sound pressure signals that are suitable for the quantification of their possible biological impact, and for conversion to source output metrics. Both applications are topic of scientific investigation. Future updates of this standard may include additional metrics. This section describes the data processing for calculating metrics related with sound pressure level ($L_{p,\mathrm{rms}}$), sound exposure level ($L_{E,p}$) and peak sound pressure level ($L_{p,\mathrm{pk}}$). Specification of the time intervals (temporal observation window (TOW) and temporal analysis window (TAW), defined in Appendix A, Table A.1) and the frequency range over which these are calculated depends on the signal type (pulse, nonpulse or continuous, see § 2.2), as well as on whether the source is moving (type A and B) or stationary (type C) during the measurements.

6.2 Metrics for pulse and nonpulse signals

The main received sound metric to be calculated for pulse and nonpulse signals is sound exposure level ($L_{E,p}$).

NOTE: Other metrics such as sound pressure level ($L_{p,\mathrm{rms}}$), peak sound pressure level ($L_{p,\mathrm{pk}}$) or SEL with a specified (auditory) frequency weighting ($L_{E,p,\mathrm{w}}$) may be required. It may also be of interest to determine additional metrics such as e.g., kurtosis, see Prior et al. (2019); Martin et al. (2020), Müller et al. (2020).

Time intervals

Definitions

- The ***temporal analysis window*** (TAW) is a time window corresponding with signals captured while the source was within the spatial Measurement Zone (see § 5.3). The TAW may include multiple pulse or nonpulse signals, as illustrated within the blue box of Figure 15.
- The ***temporal observation window*** (TOW) is a time window that contains a complete received signal or a specified fraction of a *single* pulse or nonpulse, as illustrated within the green boxes of Figure 15. The reported statistics are calculated from the metrics of multiple individual TOWs.

Specifications

- The TOW for calculating $L_{E,p}$ shall include the complete received signal of a *single* pulse or the full sequence of signals of interest for a single nonpulse transmission.
- One pass of the source through the spatial Measurement Zone may include multiple pulses or nonpulse signals, which shall be processed individually.
  - Metrics shall be calculated for each individual pulse or nonpulse.
  - Summary statistics shall be calculated from the set of all pulse or nonpulse metrics within the TAW.
  - The arithmetic mean $L_{E,p}$ and specified percentiles $L_{E,p,N\%}$ over the TAW shall be calculated.

<u>Frequency range:</u>

- $L_{E,p}$ shall be calculated over the full required frequency range (§ 5.2):
  - Minimum: decidecade bands with center frequencies from 10 Hz to 50 kHz, spanning the frequency range 8.91 Hz to 56.2 kHz.
  - Where possible: decidecade bands with center frequencies from 10 Hz to 160 kHz, spanning the frequency range 8.91 Hz to 178 kHz.
- As input for calculating source metrics, $L_{E,p}(f)$ shall be calculated for all individual decidecade bands within the full frequency range.

<u>Optional metrics:</u>

- $L_{p,\mathrm{rms}}$ shall be calculated over the same full required frequency range. The averaging time shall be specified:
  - When T_{90} (calculated according to Ainslie et al., 2018b and illustrated in Figure 16) is used, $L_{p,\mathrm{rms},T_{90}}$ shall be calculated as

$$L_{p,\mathrm{rms},T_{90}} = L_{E,p} + 10\log_{10}(0.9\ \mathrm{s}/T_{90})\ \mathrm{dB} \qquad \text{Equation 8}$$

  - When a 100 ms maximum fixed-time window (Figure 17) is used, $L_{p,\mathrm{rms,100ms}}$ shall be calculated as described in § 6.4.
- $L_{p,\mathrm{pk}}$ shall be calculated over the same full required frequency range. If required for comparison with other studies, any additional applied filtering shall be specified.
- $L_{E,p,\mathrm{w}}$ is advised to be calculated by applying a specified auditory frequency weighting function to the decidecade spectra $L_{E,p}(f)$ (Ainslie et al., 2018).

Figure 15 illustrates TAW, TOW, and the calculation of $L_{p,\mathrm{pk}}$ for a sequence of airgun pulses. Figure 16 illustrates the T_{90} time window used for calculating optional metric $L_{p,\mathrm{rms},T_{90}}$ for a single pulse or nonpulse. Figure 17 illustrates the approach to calculating optional metric $L_{p,\mathrm{rms,100ms}}$ for a single pulse or nonpulse.

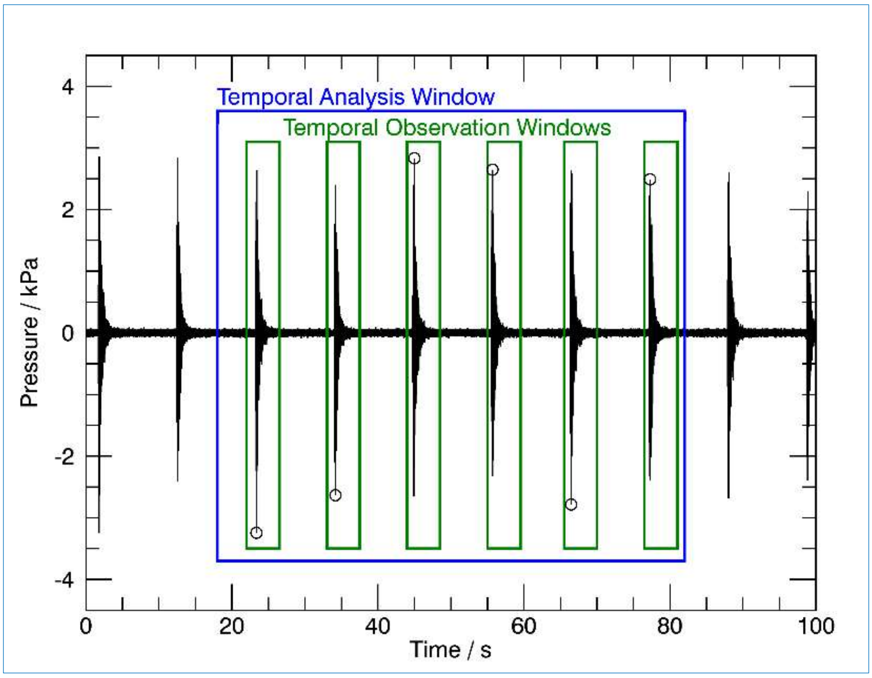

Figure 15 Illustration of time windows for pulse and non-pulse signals (example for a sequence of airgun pulses). Black curve: sound pressure time series; the black circles indicate the (compressional or rarefactional) peak sound pressures of single pulses within each individual pulse's respective TOW. Green boxes: TOW for $L_{E,p}$ for six complete pulses. The blue box spanning the six pulses represents the selected TAW, during which the source was within the spatial Measurement Zone.

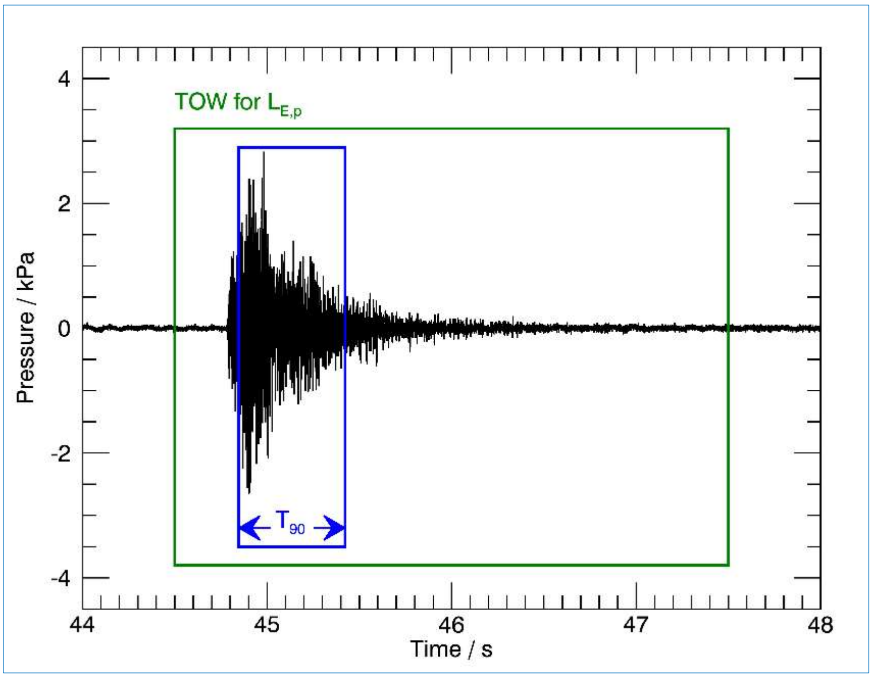

Figure 16 Illustration of relevant time windows for individual pulse and non-pulse signals (example for a single airgun pulse). Black curve: sound pressure time series; green box: TOW for $L_{E,p}$ of one complete pulse; blue box: T_{90} time window for $L_{p,\mathrm{rms},T_{90}}$.

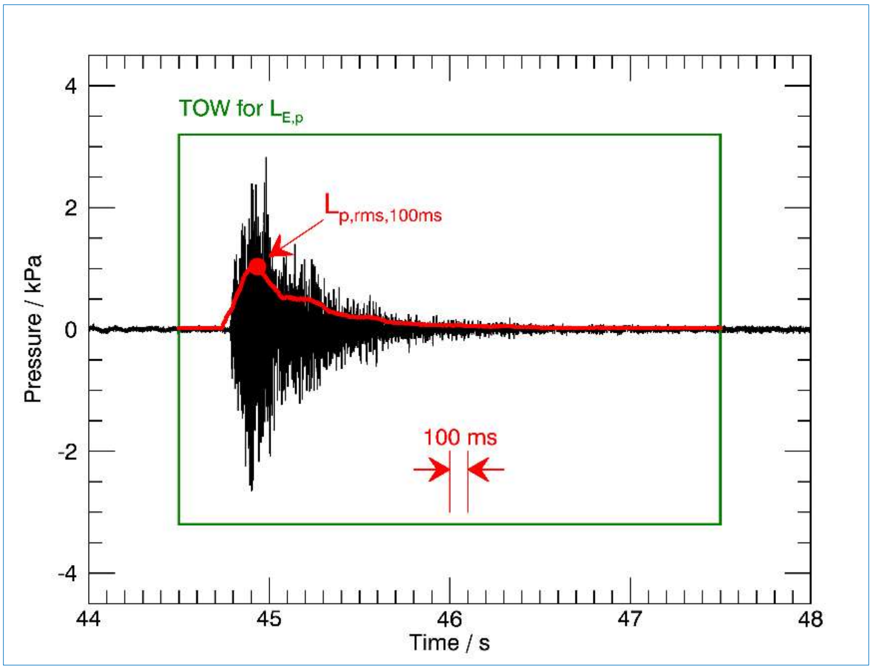

Figure 17 Illustration of the approach for calculating $L_{p,\mathrm{rms},100\mathrm{ms}}$ for individual pulse and non-pulse signals (example for a single airgun pulse). Black curve: sound pressure time series; green box: TOW for $L_{E,p}$ of one complete pulse; red curve: fixed time window SPL time series obtained by calculating $L_{p,\mathrm{rms}}$ over marched 100 ms time windows; filled red circle: maximum fixed window SPL, $L_{p,\mathrm{rms},100\mathrm{ms}}$.

6.3 Metrics for continuous signals

The main received sound metric to be calculated for continuous signals is sound pressure level ($L_{p,\mathrm{rms}}$).

<u>Time interval</u>

- For continuous signals from stationary sources (type C), $L_{p,\mathrm{rms},60\mathrm{s}}(t)$ shall be calculated over a series of time intervals (TOW, see Appendix A) $T = 60\ s$. The TOW duration is selected in correspondence with the IQOE guidelines for observation of ocean sound[4].
- The TAW (see Appendix A) over which the statistics of $L_{p,\mathrm{rms},60\mathrm{s}}(t)$ are to be determined depends on the operation of the source and shall be selected and specified by the user.
- The arithmetic mean $L_{p,\mathrm{rms},60\mathrm{s}}$ and specified temporal level percentiles $L_{p,\mathrm{rms},60\mathrm{s},N\%}$ of the time series $L_{p,\mathrm{rms},60\mathrm{s}}(t)$ shall be calculated.
  - Ideally, the full cumulative distribution function of percentiles (in 1 % steps) is calculated.
  - If the available number of time samples is smaller than 100 (TAW shorter than 100 minutes), but larger than 10, the 10th, 25th, 50th, 75th and 90th percentiles shall be calculated.

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[4] https://scor-int.org/IQOE/IQOE_2019_Standards_Workshop_Report.pdf

Frequency range

- $L_{p,\mathrm{rms,60s}}$ shall be calculated over the full required frequency range (§ 5.2):
  - Minimum: decidecade bands with center frequencies from 10 Hz to 50 kHz, spanning the frequency range 8.91 Hz to 56.2 kHz.
  - Where possible: decidecade bands with center frequencies from 10 Hz to 160 kHz, spanning the frequency range 8.91 Hz to 178 kHz.
- As input for calculating source metrics, $L_{p,\mathrm{rms,60s}}(f)$ shall be calculated for all individual decidecade bands within this frequency range.

Optional

- $L_{p,\mathrm{pk}}$ shall be calculated over the full required frequency range and over a specified time interval.
- If the measurements are intended to identify and characterize individual source mechanisms in type C sources, a higher temporal (1 s) and frequency (1 Hz) resolution may be useful.

6.4 Maximum fixed-time window SPL

The maximum fixed-time window SPL ($L_{p,\mathrm{rms,100ms,max}}$) is the maximum value of a continuous SPL function (for a specified frequency range) calculated by marching a 100 ms time window through the full TOW over which $L_{p,\mathrm{rms,100ms,max}}$ is determined. For example, a single pulse TOW is illustrated in Figure 16. The calculations are performed as follows:

- Select a TOW that contains the full duration of a single pulse or non-pulse signal, or a 60 s time interval of a continuous signal.
- Define a 100 ms fixed-time window and align that initially with the start of the TOW.
- Calculate the first value of the continuous fixed-time window SPL function within the 100 ms window as aligned in the previous bullet.
- Move the 100 ms window one time sample (time step equal to one divided by the sample rate) forward over the time series and compute the second value of the continuous fixed-time window SPL function with the shifted 100 ms window.
- Shift the 100 ms window one more time sample forward and compute the third value of the continuous fixed-time window SPL function.
- Repeat the shifting of the 100 ms window and calculation of the values of the continuous fixed-time window SPL function until the end time of the 100 ms window reaches the end time of the TOW. This completes the calculation of the continuous fixed-time window SPL function.
- Take the maximum value of the continuous fixed-time window SPL function for the selected TOW: $L_{p,\mathrm{rms,100ms,max}}$.
- Summary statistics shall be calculated from the set of maximum fixed-time window SPLs for all TOWs within a specified TAW.

6.5 Data processing steps

Starting from the digitized representation of the measured sound pressure at the output of the ADC at the end of the measurement chain (Chapter 3), the following data processing steps are required (based on ISO 18406):

1 Inspect the digitized time signals of the hydrophone recordings obtained over a discrete time series, t, where t_i corresponds to the i^{th} point in the time series.
  a. Confirm that these data exhibit the expected sounds.
  b. If there are unexpected disturbances, or if the signals show signs of "clipping" (overloading the maximum allowed amplitude of the measurement chain), then these parts of signal are not suitable for analysis and should be discarded.

2 If required, apply digital low-, high-, or band-pass filtering to the data, to limit the frequency content of the signal to the overall band of interest.

3 Convert the digitized time signal $N(t_i)$ to system-weighted sound pressure, $p_{\text{sw}}(t_i)$, by dividing by the total system sensitivity, M_{tot} in 1/Pa (defined in Appendix A, Table A.5):

$$p_{\text{sw}}(t_i) = n(t_i)/M_{\text{tot}} \qquad \text{Equation 9}$$

  a. If the response characteristics of the measurement chain are not uniform in the frequency range of interest, then an appropriate frequency-dependent correction shall be applied in processing step 8.

4 Select periods of the signals for further analysis (each representing a specified TAW, containing a series of specified TOWs, depending on the signal type):
  a. Select TOW (duration T) within which all of an identifiable signal is contained.
  b. Select corresponding noise TOW (duration T) during which the signal is absent. The duration of the noise TOW should be equal to the duration of the signal TOW. To get a more stable estimation of the noise level, we suggest calculating the arithmetic mean SPL over a noise TAW that contains at least 10 noise TOWs
  c. If acoustic pulses or pulse trains are to be characterized, these can be found either by visual inspection of the waveform, or in an automated manner using a routine that checks where the recorded signal exceeds a given threshold.
    i. Identify and isolate the specific periods of the waveform to be analyzed containing the data of interest.
    ii. These may be periods containing individual acoustic pulses or sequences of multiple pulses:
      - Pulse signals should contain only a single pulse
      - Intermittent pulse train could contain multiple pulses
      - Nonpulse signal could contain multiple pulse

The next steps shall be repeated for each selected TOW, for signal as well as noise.

5 If required, determine the maximum system-weighted sound pressure (peak system-weighted sound pressure $p_{\mathrm{pk,sw}} = \max(|p_{\mathrm{sw}}(t)|)$) within each TOW. The corresponding peak sound pressure level is:

$$L_{p,\mathrm{pk,sw}} = 10\log_{10}\left(p_{\mathrm{pk,sw}}^2 / p_0^2\right)\ \mathrm{dB} \qquad \text{Equation 10}$$

a. For sufficiently broadband acquisitions systems, the peak sound pressure and peak sound pressure level can be approximated using

$$p_{\mathrm{pk}} \approx p_{\mathrm{pk,sw}} \qquad \text{Equation 11}$$

$$L_{p,\mathrm{pk}} \approx L_{p,\mathrm{pk,sw}} \qquad \text{Equation 12}$$

The accuracy of these approximations can be affected by the bandwidth and frequency response of the measuring system. The frequency response magnitude is ideally invariant with frequency to within a tolerance of 2 dB in the full frequency range. For best accuracy, influences that cause fluctuations in the frequency response are ideally avoided, examples being resonances in the hydrophone response or application of digital filtering within the overall frequency range.

6 Optionally, broadband sound pressure level and sound exposure level can be calculated directly from the pressure time signal. However, frequency spectra of these metrics are preferred for the conversion to source output metrics, to account for frequency dependence in propagation loss as well as for possible frequency-dependent calibration corrections. Broadband sound pressure level and sound exposure level can be calculated from these frequency spectra (processing step 13).

7 Convert the time waveform in each selected TOW to a single sided mean-square sound pressure spectral density spectrum $\overline{p_f^2}(f_i)$, applying a discrete Fourier transform (DFT).

a. for pulse and nonpulse signals, it is recommended to apply the DFT to the specified TOW, using a flat top time window.

b. for continuous signals it is recommended to apply the DFT to 1 s windows, using a Hann time window with a 50 % overlap, and then average the resulting spectra over the 60 s TOW.

8 If frequency-dependent calibration corrections are required, apply them by multiplying the spectral density $\overline{p_f^2}(f_i)$, with a frequency spectral representation of the squared modulus of the system sensitivity (spectral system sensitivity, see Appendix A, Table A.5) relative to the single number sensitivity that was used for the conversion in processing step 3: $|M(f_i)|^2/M_{\mathrm{tot}}^2$.
This calibration can also be applied after the next step, using the mean sensitivities for each of the frequency bands.

9 Calculate the signal and noise SPL decidecade spectra $\overline{p_f^2}(f_j)\Delta f_j$ by summing the amplitudes $\overline{p_f^2}(f_i)$ of the individual frequency bins f_i that lie within each decidecade band (see Appendix B), multiplied by the decidecade bandwidth Δf_j.

10 Compare corresponding signal and noise spectral densities:

   a. If $\overline{p_{f,\mathrm{S+N}}^2}(f_j) \leq 2\,\overline{p_{f,\mathrm{N}}^2}(f_j)$ discard the measurement in frequency band f_j.

   b. If $\overline{p_{f,\mathrm{S+N}}^2}(f_j) > 2\,\overline{p_{f,\mathrm{N}}^2}(f_j)$, correct by subtracting the noise:

$$\overline{p_{f,\mathrm{S}}^2}(f_j) = \overline{p_{f,\mathrm{S+N}}^2}(f_j) - \overline{p_{f,\mathrm{N}}^2}(f_j) \qquad \text{Equation 13}$$

   c. Step b may be omitted when $\overline{p_{f,\mathrm{S+N}}^2}(f_j) > 10\,\overline{p_{f,\mathrm{N}}^2}(f_j)$, so that

$$\overline{p_{f,\mathrm{S}}^2}(f_j) \approx \overline{p_{f,\mathrm{S+N}}^2}(f_j) \qquad \text{Equation 14}$$

11 Optionally, this background noise correction can also be applied to the narrowband spectra, before the conversion to decidecade bands (processing step 9).

12 Calculate the received sound metrics (decidecade spectra) for each selected TOW, T_n:

   a. For continuous signals: calculate the signal sound pressure level decidecade spectrum:

$$L_{p,T_n}(f_j) = 10\log_{10}\left(\overline{p_{f,\mathrm{S}}^2}(f_j)\,\Delta f_j/p_0^2\right)\ \mathrm{dB} \qquad \text{Equation 15}$$

   b. For pulse and nonpulse signals: calculate the signal sound pressure exposure level decidecade spectrum:

$$L_{E,T_n}(f_j) = 10\log_{10}\left(\overline{p_{f,\mathrm{S}}^2}(f_j)\,\Delta f_j\,T_n/p_0^2 t_0\right)\ \mathrm{dB} \qquad \text{Equation 16}$$

13 Calculate broadband sound pressure level and sound exposure level, by summing of the decidecade spectral components over the full frequency range § 5.2.1:

$$L_{p,T_n} = 10\log_{10}\left(\sum_j \overline{p_{f,\mathrm{S}}^2}(f_j)\,\Delta f_j\ /p_0^2\right)\ \mathrm{dB} \qquad \text{Equation 17}$$

$$L_{E,T_n} = 10\log_{10}\left(\sum_j \overline{p_{f,\mathrm{S}}^2}(f_j)\,\Delta f_j\,T_n/p_0^2 t_0\right)\ \mathrm{dB} \qquad \text{Equation 18}$$

7 Calculation of source output metrics

To acoustically characterize the OGP sources in terms of metrics that can be used as input for environmental impact assessments for future projects, the influence of the specific environment in which the source output was measured and of the measurement equipment and geometry are ideally removed from the measurement results. This section provides the calculation procedures to determine source metrics from received sound metrics (Chapter 6).

7.1 General source metrics

Because the measurements are taken in the far field (§ 5.3.3), the source can be represented as a 'point source' (see § 2.3), with specified three-dimensional coordinates relative to the geometry of the actual source.

The source properties of the underwater sound source types in this study generally depend on time, frequency, and direction.

- Time dependence is captured by the statistics of the selected source metrics.
- Frequency dependence is captured by the selected frequency bandwidth(s) and weighting.
- Directional dependence is captured by selecting appropriate 'aspect angles' for the source metrics, per source type.

For the purpose of characterizing the OGP sources in relation to environmental impact, the focus is on characterizing the source for a limited range of vertical angles (close to the horizontal) and a limited set of azimuthal angle ranges (e.g., 'bow', 'port abeam', 'stern' and 'starboard abeam' aspects).

7.1.1 Source metric for continuous signals

By definition (ISO 18405, see Appendix A, Table A.2), source level (L_S) is the sum of SPL (L_p) and propagation loss (N_{PL}) for the measurement environment and geometry:

$$L_S = L_p + N_{\mathrm{PL}} \qquad \text{Equation 19}$$

L_p and N_{PL} are frequency-dependent, hence the L_S calculation needs to be performed in the frequency domain.

7.1.2 Source metric for pulse and nonpulse signals

The 'energy source level' (ESL) ($L_{S,E}$) for pulse and nonpulse sources is defined (ISO 18405) as the sum of SEL (L_E) and propagation loss ($N_{\mathrm{PL},E}$) for the measurement environment and geometry:

$$L_{S,E} = L_E + N_{\mathrm{PL},E} \qquad \text{Equation 20}$$

L_E and $N_{\mathrm{PL},E}$ are frequency-dependent, hence the $L_{S,E}$ calculation needs to be performed in the frequency domain.

ISO 18405 provides no definition for source metrics resulting from measurements of zero-to-peak sound pressure level.

7.1.3 *Propagation Loss*

PL is usually assumed to be a frequency-dependent, invariant property of the environment and geometry over the duration of the measurement period. The same frequency spectrum of PL can be applied to the frequency spectrum of SL metrics.

PL can be determined from:

- Measurements on a source with a known SL, in the same environment with the same measurement geometry. Note: In an environment with multi-path propagation, the three-dimensional directionality of this source needs to be representative of the directionality of the actual source to determine the appropriate PL.
- An appropriate numerical propagation model that accounts for source and receiver geometry, sea surface and seabed reflections, and acoustic absorption, where possible validated (or calibrated) for the measurement environment.
- An appropriate semi-empirical (‘practical spreading law’) model, calibrated by measurements at multiple distances from the source.

Frequency domain representations of N_{PL} and $N_{\mathrm{PL},E}$ for the same measurement geometry and environment are equal.

7.2 Seismic (type A) pulse and nonpulse source metrics

7.2.1 *Required Metrics*

The required metrics for type-A sources are average and quartile decidecade band and broadband ESL for each of the required aspect measurement geometries.

For the chosen measurement geometry, decidecade and broadband ESLs are first calculated for all individual pulses in the respective TAW and over all hydrophones. The 10th, 25th, 50th, 75th, and 90th percentile levels are calculated from the distribution of the individual ESLs. The average decidecade and broadband ESLs are calculated as power averages respectively of the individual pulse-hydrophone decidecade and broadband ESLs.

7.2.2 *Source Location for spatially distributed sources*

The 3-dimensional point source location for the calculation of $N_{\mathrm{PL},E}$ for spatially distributed sources, i.e., where the source is comprised of multiple sound-generating elements, is the weighted average location of the elements. The weighting coefficient w_i for source element i will be chosen to represent the normalized fraction of the element’s acoustic energy or power relative to that of the entire source. For airgun arrays, the weighting coefficient for each airgun will be the individual chamber volume divided by the sum of the chamber volumes of all airguns.

The point source location coordinates (S_x, S_y, S_z) are calculated as follows:

$$S_x = \sum_i w_i s_{i,x}$$

$$S_y = \sum_i w_i s_{i,y}$$

$$S_z = \sum_i w_i s_{i,z}$$

where $s_{i,x}, s_{i,y}, s_{i,z}$ are the $x, y, \text{and}\ z$ coordinates of the i^{th} source element.

7.2.3 *Propagation Loss*

PL $N_{\text{PL},E}(f, S_z, D, R)$ for type A sources shall be obtained for a point source based on a full-wave acoustic model or from propagation loss measurements made at the same site where the source measurements are made. It shall be calculated or measured as the power average of PL over at least ten frequencies within the decidecade frequency band having center frequency f and for the source depth S_z, hydrophone depth D, and the true horizontal offset distance R at the half-duration time of the respective pulse or nonpulse. Suitable models include finite difference and wavenumber integral approaches (Jensen et al., 2011) for frequencies less than 1 kHz, and ray trace models at higher frequencies. When water depths are shallow, seabed reflected and refracted acoustic energy may affect PL and, in these cases, it is important that the model accounts for seabed acoustic interactions. Consequently, the geoacoustic properties of the seabed, including compressional and shear wave speed profiles, compressional and shear wave attenuation profiles, and density profile will be required as model inputs.

7.2.4 *Calculation of Metrics*

The decidecade ESL, $L_{S,E}(f)$ for each pulse or non-pulse signal is first calculated from the sum of its decidecade sound exposure level $L_E(f)$, as determined per § 6.5, and PL, $N_{\text{PL},E}(f, S_z, D, R)$ per § 7.2.3. The ESL for the i^{th} pulse or nonpulse measured on the j^{th} hydrophone will thus be obtained from:

$$L_{S,E,i,j}(f) = L_{E,i,j}(f) + N_{\text{PL},E,i,j}(f) \qquad \text{Equation 21}$$

The reported average decidecade ESL of the source, for each required measurement geometry, will be the power average ESL of the N individual pulses or nonpulses inside the TAW, or possibly from more than one TAW if multiple measurement passes are made, measured on all M hydrophones of the measurement geometry:

$$L_{S,E}(f) = 10 \log_{10}\left(\frac{1}{NM}\sum_{i,j} 10^{[L_{E,i,j}(f)+N_{\text{PL},E,i,j}(f)]/(10\ \text{dB})}\right) \text{dB} \qquad \text{Equation 22}$$

The reported broadband ESL for the source will be calculated as the sum of the decidecade ESL over all K frequency bands:

$$L_{S,E} = 10 \log_{10}\left(\sum_k 10^{[L_{S,E}(f_k)]/(10\ \text{dB})}\right) \text{dB} \qquad \text{Equation 23}$$

Quartile (25th, 50th and 75th percentile) decidecade and broadband ESL should be reported if there are at least six signal measurements (i.e., $\boldsymbol{N} \times \boldsymbol{M}$>5). If there are less than 6 signal measurements, then the individual signal decidecade spectra should be plotted and the broadband ESL values tabulated.

7.3 Geophysical engineering surveys (type B) pulse and nonpulse source metrics

7.3.1 Required Metrics

The required metrics for type B sources are decidecade band and broadband energy source level ESL for each of the required aspect measurement geometries.

For the chosen measurement geometry, these metrics are calculated for the individual ESLs of all pulses in the respective TAW and for all hydrophones.

7.3.2 Propagation Loss

For HRG sources use $N_{\mathrm{PL},E} = 20 \log r \ \mathrm{dB} + \alpha(F) r$, where F is the center frequency (in kilohertz) of the corresponding band per § 5.2.1, and r is the slant range in meters. For frequencies above 10 kHz the absorption coefficient in dB/m may be approximated as $\alpha/(\mathrm{dB\ m^{-1}}) = 3.39 \cdot 10^{-7} F^2 + 4.85 \cdot 10^{-2} F^2/(F^2 + 75.6^2)$. This formula for the absorption is obtained by neglecting the first term of Eq. (2.2) of Ainslie (2010), which is negligible at frequencies above 10 kHz. The formula is applicable to conditions corresponding to a seawater salinity of 35 psu and temperature of 10 °C. For situations that depart from these conditions, or for a center frequency below 10 kHz, the formula of Francois and Garrison (1982a) or van Moll et al. (2009) may be used.

7.3.3 Calculation of Metrics

Continuing from data processing steps in § 6.5 for decidecade L_E,

- Calculate the single pulse or nonpulse decidecade ESL for each signal within the TAW, per Equation 20
  - Calculate $N_{\mathrm{PL},E}(f)$ per § 7.3.2 for all required decidecade bands, noting f indicates the band center frequency in Hz, per § 5.2.1.
  - Calculate decidecade band ESL $L_{S,E}(f)$ by summing decidecade L_E and $N_{\mathrm{PL},E}$, i.e.,

$$L_{S,E}(f) = L_E(f) + N_{\mathrm{PL},E}(f) \qquad \text{Equation 24}$$

- Calculate broadband ESL for each signal by summing the decidecade ESL:

$$L_{S,E} = 10 \log_{10}\left(\sum_k 10^{[L_{S,E}(f_k)]/(10\ \mathrm{dB})}\right) \mathrm{dB} \qquad \text{Equation 25}$$

- Plot broadband ESL versus azimuthal angle θ (Figure 3) of each signal for abeam measurement hydrophones.
  - Use appropriate angle ranges in plots to illustrate beam characteristics such as beam width and sidelobes, if present.
- Plot broadband ESL versus off-vertical angle ϕ (Figure 3) of each signal for keel measurement hydrophone.
  - Use appropriate angle ranges in plots to illustrate beam characteristics such as beam width and sidelobes.
- If present, estimate 3 dB and 10 dB beam widths from the plot of broadband ESL versus angle.
- Find maximum side-lobe broadband ESL level and corresponding angles θ and ϕ, if present.
- Find the maximum ESL over angle and hydrophone.

7.4 Production platform (type C) source metrics

Two different type C source configurations are considered:

1. floating platforms in deep water (Figure 3, top);
2. bottom mounted platforms that extend over the water depth (Figure 14).

The source level of a floating platform can be determined following the approach for measuring ship source level (ISO 17208-1 and 17208-2) when measured in deep water. The source level can be defined in shallow water as well, however, the procedure for measuring ship source level in shallow water is still under development (ISO 17208-3).

For bottom-mounted platforms in shallow water, calculation of source metrics faces the same problems as observed for offshore pile driving. The scope of the ISO standard for measuring radiated underwater sound from percussive pile driving (ISO 18406) does not include the calculation of source level metrics. The Annex to ISO 18046 explains that it is not yet clear how to provide an entirely robust definition of source level for percussive pile driving. Sound sources that penetrate both the water surface and the seabed are intimately connected to the environment. This means that if the environment changes, so does the source output. Hence these sources cannot be properly characterized independent of the environment in which they operate. Nevertheless, source characterization may be required to map the sound distribution around their operational location. In that case, it is advised to adopt an approach based on inter- and extrapolation of the received sound metrics at the measurement locations to the sound map of the environment.

7.4.1 Required Metrics

The required metrics for type C sources are decidecade band and broadband source level SL for each of the required aspect measurement geometries, as a function of the operation of the source. Temporal variations of the source characteristics associated with operational variations shall be obtained from the measurements at a fixed representative position during the full measurement period. Temporal variations at nominally equal operational condition are reported in terms of percentiles of the measured decidecade band and broadband source level SL.

7.4.2 Propagation Loss

- Propagation loss for ‘floating platform’ sources in deep water can be estimated using the approach described in ISO 17208-2.
- Propagation loss for ‘floating platform’ sources in shallow water shall be obtained for a point source at a specified depth, based on a full-wave acoustic model.
- For ‘bottom-mounted platforms’, propagation loss shall be calculated with an appropriate semi-empirical (‘practical spreading law’) model, following the guidance provided by Ainslie et al., 2014 and calibrated by measurements at multiple distances from the source.

7.4.3 Calculation of Metrics

Calculate decidecade band SL $L_S(f)$ by summing decidecade L_p and N_{PL}, i.e.,

$$L_S(f) = L_p(f) + N_{\mathrm{PL}}(f) \qquad \text{Equation 26}$$

Calculate broadband SL for each signal by summing the decidecade SL:

$$L_S = 10 \log_{10}\left(\sum_k 10^{[L_S(f_k)]/(10\ \mathrm{dB})}\right) \mathrm{dB} \qquad \text{Equation 27}$$

8 Uncertainties

When evaluating uncertainty, there are a number of steps recommended (source: ISO 18406).

Check for any spurious artefacts and eliminate spurious signals:
- try to estimate any residual effects.

Assess the uncertainty in the instrument calibration:
- check that this is valid across the entire frequency range.

Check for consistency in the results, for example:
- between hydrophones deployed at similar ranges;
- do the measurements vary with position or range as expected?
- are there anomalous results in the data set?

Check any assumptions made:
- is it possible to assign uncertainties to these assumptions?

Consider conducting a sensitivity analysis:
- involves varying the input parameters (for example, to a model or calculation) and determining the sensitivity of the results to these changes.

List uncertainty contributions and assign values.

Combine the uncertainties according to the ISO/IEC Guide 98-3.

9 Reporting

9.1 General reporting requirements

Reporting of measurement for the three source types shall follow the Phase 1 Reporting standard (Ainslie & de Jong, E&P Sound and Marine Life JIP Standard: Underwater Acoustics – Task 3: Reporting, 2018).

Source type specific reporting requirements are listed is the following sections. The minimum requirements for reporting source measurements for all source types include:

- Source description (including operating conditions and settings).
- Specifications of all measurement instrumentation components, sampling rate, settings (Chapter 3):
  - type of calibration performed on measurement system and results;
  - recording settings (sample rate, filter characteristics).
- UTC time stamp of reported measurements (ISO 8601).
- Measurement locations.
- Measurement geometries used (include hydrophone depths and mooring descriptions).
- CPA for types A and B or measurement distance for type C sources.
- Description of environmental conditions (§ 5.8).
- Water depth (include tidal variations).
- Wave height and/or wind speed (with measurement height).
- Sound speed and absorption profiles (temperature and salinity) over the water depth (§ 5.8.3).
- Seabed type at the measurement location (e.g., compressional and shear wave speed and attenuation profiles, and density profile, or sediment properties including layering).
- Water depth at source and hydrophone location, and seabed slope, described by strike and dip[5].
- Presence of other sound sources than the source that is being measured (e.g., vessels, marine animals, construction, or surveying activities, etc.).
- Data processing settings (Chapter 6; and Ainslie et al., 2018b):
  - time windows;
  - calibration corrections;
  - frequency band.
- Measured background noise metrics and applied background corrections, where appropriate, and the frequency band.
- Sound field metrics, and the frequency band, and averaging time.
- Propagation Loss calculation (Chapter 7):
  - full description of the applied method, modeling or measurement;
  - including all details about selected model input parameters;
  - verification and validation.
- Source output metrics (including description of conversion procedure and source depth), and the frequency band, and averaging time, and associated source depth.

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[5] https://en.wikipedia.org/wiki/Strike_and_dip

For all the listed source metrics:

- the time interval and frequency range over which they are calculated;
- the direction from the source;
- decidecade band and broadband source metrics;
- dependent on the number of captured samples of the source metric, the 25th, 50th, and 75th temporal level percentiles (quartiles) of source metrics should be reported, as well as the power average. Where the number of samples is sufficiently high, reporting the 1st, 5th, 10th, 90th, 95th, and 99th temporal level percentiles should also be considered for reporting.

9.2 Reporting of type A (geophysical exploration surveys) source information

In addition to the requirements at the beginning of this section, for type A sources, also report source element descriptions including device brand, model number, manufacturer’s specifications for source pressure emission levels and descriptions of any modifications made to the source.

If a source is a custom system with specifications not available from a manufacturer, the source characteristics should be provided, including a full description of its method of sound pressure production and all parameters that might affect the produced sound characteristics.

Operating conditions for airguns should include operating pressure, water temperature, port-size, source repetition rate or pulse interval, shot point interval, operating depth, and tow speed.

Operating conditions for electroacoustic sources and marine vibrator sources should include selected waveform type, controllable source parameters such as frequency, energy, voltage, signal duration, sweep type, signal repetition rate or pulse interval distance, and operating tow depth and speed.

When source elements are operated in arrays, additional information should be recorded, including spatial coordinates of the positions of all operating and spare elements in the array, and whether the elements are single airguns or clustered airguns. The array geometry should be specified by coordinates (x,y,z) of each element, where x indicates the in-line (parallel to tow direction) measured aft of the frontmost operating element. The y dimension is the distance starboard of the nominal center of its lateral extent, with preference for the origin given to the center string in the case of an odd number of strings and to the mid-point of the two innermost strings in the case of an even number of strings. The z coordinate is given by the depth of each element below the nominal water surface.

For each measurement pass, provide:

- tow speed and tow path direction;
- position of CPA to hydrophones.

As per § 7.2, the required metrics for type A sources are average and quartile decidecade ESL and broadband ESL. These values are to be provided in tabular format. The average decidecade spectra should also be plotted versus frequency band center frequency. If there are less than 6 measurements of ESL for a given aspect geometry, the individual measured decidecade spectra should be plotted versus frequency band center frequency.

The optional metrics of peak compressional or rarefactional pressure and SPL_{T90} (§ 6.2) and maximum fixed time window SPL (§ 6.4) for all measured signals should be plotted as a function of absolute source-hydrophone slant range distance, with different hydrophone depths indicated by different symbols.

9.3 Reporting of type B (geophysical engineering surveys) source information

In addition to the requirements at the beginning of this section, for type B sources, also report:

- HRG source make and model.
- All operational settings, e.g.,
  - source signal and frequency range;
  - pulse firing rate;
  - nominal pulse duration;
  - power level.

HRG source metrics shall include the following:

1. Plot sound pressure time series through TAW for each measurement geometry (§ 6.2).
2. Plot decidecade energy spectrum for the pulse or nonpulse with the highest ESL within the TAW (§ 7.3.3).
3. Report the single pulse or nonpulse broadband SEL, by summing the decidecade SEL values (§ 6.5):
   a. Plot the broadband SEL versus time (Figure 18);
   b. Plot optional metrics versus time and versus slant range.
4. Plot the single pulse or nonpulse decidecade ESL for each signal within the TAW, per Equation 20:
   a. for HRG sources use $N_{\text{PL},E} = 20 \log r \text{ dB} + \alpha(F) r$ per § 7.3.2;
   b. Use frequency bands per § 5.2.1.
5. For the single pulse or nonpulse broadband ESL for each signal within the TAW:
   a. Plot ESL versus azimuthal angle θ (Figure 3) of each signal for abeam measurement hydrophones. Use appropriate angle ranges in plots to illustrate beam characteristics such as beam width and sidelobes, if present;
   b. Plot ESL versus off-vertical angle θ (Figure 3) of each signal for keel measurement hydrophone. Use appropriate angle ranges in plots to illustrate beam characteristics such as beam width and sidelobes, if present;
   c. Estimate and report 3 dB and 10 dB beam widths;
   d. Find and report maximum side-lobe level and corresponding angles θ and ϕ, if present;
   e. Optional, plot in 3-dimensions, versus the θ and ϕ.
6. Report the maximum measured ESL over angle and hydrophone.
7. Plot the decidecade ESL versus band center frequency for the pulse or nonpulse with the maximum broadband ESL (Figure 19).
8. Optional metrics to report may include, $L_{p,\text{rms},T_{90}}$, $L_{p,100\text{ms},\text{max}}$, $L_{p,\text{pk}}$; per § 6.2 and § 6.4. These metrics should be plotted as a function of absolute source-hydrophone slant range distance, with different hydrophone depths indicated by different symbols.

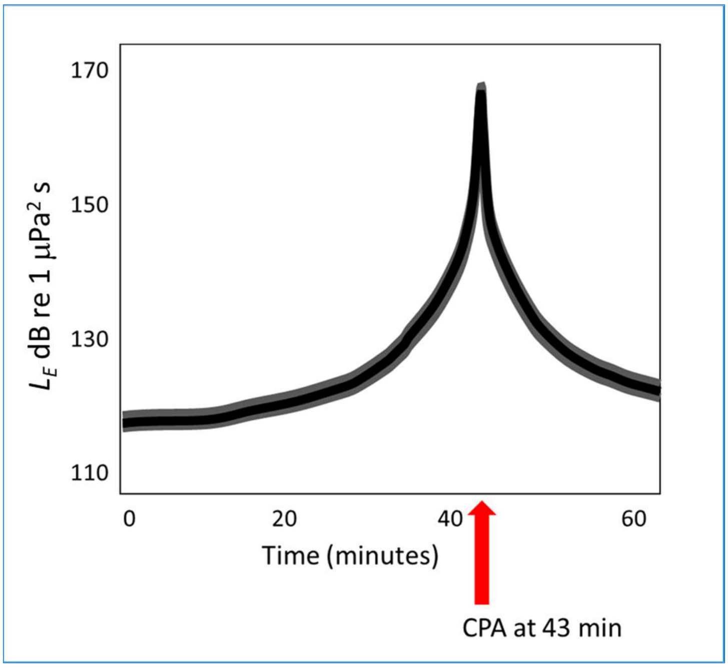

Figure 18 Illustrated SEL as a function of time for an HRG source. The CPA time is approximately 43 min.

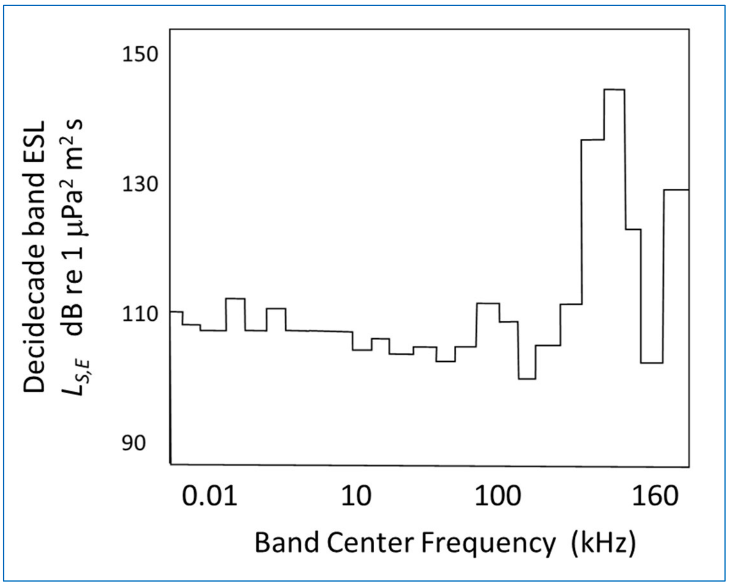

Figure 19 Illustrated (user to specify) decidecade band $L_{S,E}$ over a time window encompassing a single pulse or nonpulse with the maximum level, for an HRG source signal.

9.4 Reporting of type C source (production activities) information

In addition to the requirements at the beginning of this section, for type C sources, also report a detailed description of the production facility.

- Log of production activities over the measurement period.
- Details of production activities and settings, e.g.,
  - Operational equipment;
  - Equipment power settings and revolution rates.

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11 Signature

The Hague, July 2021

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A Terminology

The purpose of this appendix is to clarify the meaning of some of the terms used in the rest of this report. The terminology of the JIP terminology standard (Ainslie et al., 2020) and the international standard for underwater acoustical terminology (ISO, 2017) are followed throughout. The JIP terminology standard is compliant with ISO (2017).

A.1 Acoustics (sound field characterization)

Terminology for sound field characterization is defined in Table A.1.

Table A.1 Acoustical terminology for sound field characterization.

Term	**Definition**
decidecade **synonym**: one-third octave (base-10)	ISO 18405 (3.1.4.2)
sound pressure level **synonym**: mean-square sound pressure level, root-mean-square sound pressure level	ISO 18405 (3.2.1.1) **NOTE**: continuous
sound pressure exposure level **synonym**: time-integrated squared sound pressure level, sound exposure level	ISO 18405 (3.2.1.5) **NOTE**: pulse or nonpulse
zero-to-peak sound pressure level	ISO 18405 (3.2.2.1)
peak compressional sound pressure level	ISO 18405 (3.2.2.2)
peak rarefactional sound pressure level	ISO 18405 (3.2.2.3)
root-mean-square sound pressure **abbreviation**: rms sound pressure	square root of the mean-square sound pressure
measurement zone	spatial extent of the region within which measurements are made for source types A and B (Figure 7) **NOTE**: The length of the measurement zone is $2R/\sqrt{3}$, where R is the horizontal range at CPA.
temporal observation window **acronym**: TOW	interval of time within which metrics of the sound field are calculated or estimated **BASED ON**: Ainslie et al. (2020) (Table 4)
temporal analysis window **acronym**: TAW	interval of time containing multiple temporal observation windows over which statistics of the sound field metrics are calculated **BASED ON**: Ainslie et al. (2020) (Table 4)
signal analysis window	temporal analysis window containing one or more signals
noise analysis window	temporal analysis window containing only noise

Term	**Definition**
Nth temporal SPL percentile	value of mean-square sound pressure level below which N% of observations fall, in a specified temporal analysis window **NOTES**: based on Ainslie et al. (2020) (Table 23)
Nth temporal SEL percentile	value of mean-square sound exposure level below which N% of observations fall, in a specified temporal analysis window
maximum root-mean-square sound pressure **abbreviation**: maximum rms sound pressure	largest value of root-mean-square sound pressure in a specified temporal analysis window
maximum sound pressure level	largest value of sound pressure level in a specified temporal analysis window **NOTES**: maximum sound pressure level is the level of the maximum root-mean-square sound pressure, not to be confused with peak sound pressure level, representing instantaneous pressure.

Metrics used to categorize a sound signal are listed in Table A.2.

Table A.2 Acoustical terminology for signal characterization.

term (symbol)	**definition**
pulse	signal satisfying the condition τ < 125 ms and $T - \tau$ > 1000 ms
nonpulse	signal satisfying the condition τ > 1000 ms and $T - \tau$ > 1000 ms
continuous signal	signal satisfying the condition $T - \tau$ < 125 ms
signal train	sequence of multiple signals
pulse train	sequence of multiple pulses
nonpulse train	sequence of multiple nonpulses
signal repetition rate **synonym**: signal repetition frequency **symbol**: ν	rate at which signals are transmitted in a signal train **NOTE**: The signal repetition rate is equal to the number of signals in a given time interval divided by the duration of the time interval.
signal repetition period **synonym**: signal repetition interval **symbol**: T	reciprocal of the signal repetition rate $T = 1/\nu$ **NOTE**: The signal repetition period is equal to the time from the start of one signal to the start of the next.
signal duration **symbol**: τ	time interval between signal start and signal end
inter-signal interval	difference between signal repetition period and signal duration $T - \tau$ **NOTE**: The inter-signal interval is equal to the time from the end of one signal to the start of the next.
Nyquist rate **unit**: Hz	twice the maximum signal frequency **NOTES**: The Nyquist rate is a property of the signal. See also *Nyquist frequency* (Table A.4).

A.2 Acoustics (source characterization)

The basic building blocks for characterizing underwater sound sources are the source waveform, $s(t)$ and its Fourier transform the source spectrum, $S(f)$ (ISO, 2017). These building blocks can be used to define the source level. Metrics used to categorize a source signal are listed in Table A.3.

Table A.3 Acoustical terminology for source characterization.

Term (symbol)	Definition
source level (SL) **symbol**: L_S **unit**: dB	$10\log_{10}\frac{\frac{1}{T}\int_{-T/2}^{+T/2} s(t)^2\,\mathrm{d}t}{s_0^2}$ dB **reference value**: $s_0^2 = 1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2$ **NOTE**: From ISO 18405.
energy source level (ESL) **synonym**: total energy source level **symbol**: $L_{S,E}$ **unit**: dB	$10\log_{10}\frac{\int_{-\infty}^{+\infty} s(t)^2\mathrm{d}t}{s_0^2\ t_0}$ dB **reference value**: $s_0^2\ t_0 = 1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s}$ **NOTE**: From ISO 18405. The limits of integration are stated as $-\infty$ to $+\infty$ to indicate that all transient energy is included, consistent with note 6 to entry 3.3.1.5.
energy source spectral density level **synonym**: total energy source spectrum level; energy source spectrum level (ESSL) **symbol**: $L_{S,E,f}$ **unit**: dB	$10\log_{10}\frac{2\lvert S(f)\rvert^2}{s_0^2\ t_0/f_0}$ dB **reference value**: $s_0^2\ t_0/f_0 = 1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s/Hz}$ **NOTE**: Based on Ainslie et al. (2020)
geometric near field	region close to a sound source within which the distances of different source elements from the field point cannot be treated as equal **SOURCE**: Adapted from Morfey (2001), p174 **NOTE**: In the geometric near field the contribution from each source element cannot be adequately represented by weighting according to the reciprocal of the distance to the center of the source region.
Fresnel near field	region far enough from a sound source to be outside the geometric near field, but not far enough for the Fresnel correction to be neglected **SOURCE**: Adapted from Morfey (2001), p167 **NOTES**: In the Fresnel near field the sound pressure amplitude is not inversely proportional to range. For a definition of *Fresnel correction*, see Morfey (2001).
hydrodynamic near field	region close to a sound source within which the particle velocity and the pressure are nearly in quadrature **SOURCE**: Adapted from Morfey (2001), p189 **NOTE**: See also Morse and Ingard, p311
acoustic far field	spatial region in a uniform medium where the direct-path field amplitude, compensated for absorption loss, varies inversely with range **SOURCE**: ISO 18405 **NOTES**: According to ANSI S1.20-1988 (R2003), far-field conditions exist when the distance from the source exceeds the larger of $\pi A^2/4\lambda$ and $A/2$, where A is the size of the source and λ is the acoustic wavelength: "Beyond this minimum distance from a circular piston or

Term (symbol)	Definition
	line source, the sound pressure at a point receiver will be within 4 % of that calculated assuming spherical divergence.” A fractional error of 4.0 % in rms sound pressure corresponds to a 0.34 dB error in SPL. According to IEC 60565:2007, far-field conditions exist when the distance from the source exceeds the larger of A^2/λ and $5A$: “the distance shall be chosen [to exceed this minimum distance] in order to reduce the error due to lack of spherical divergence to below 0.3 dB.” A 0.3 dB error in SPL corresponds to a fractional error of 3.5 % in rms sound pressure.

A.3 Data acquisition

Terminology for data acquisition is defined by the ADEON terminology standard (Ainslie et al., 2020), see Table A.4.

Table A.4 Terminology for data acquisition.

Term	Definition
ADC input	generic term referring to an analogue representation of the time-varying current or voltage entering the ADC **SOURCE**: ADEON (Ainslie et al., 2020)
ADC output **synonym**: system output	generic term referring to a digital representation of the ADC input, suitable for storage in a digital storage medium or processing on a digital computer **SOURCE**: ADEON (Ainslie et al., 2020)
bit depth **synonym**: word size **symbol**: N_{bit} **unit**: bit	number of bits at ADC output used to represent one value of ADC input **SOURCE**: ADEON (Ainslie et al., 2020)
ADC dynamic range **symbol**: $\Delta L_{\mathrm{DR,ADC}}$	the quantity $\Delta L_{\mathrm{DR,ADC}} = 10 \log_{10} \frac{\overline{v_{\mathrm{FS}}^2}}{v_{\mathrm{N,eq,self}}^2}$ dB, where $\overline{v_{\mathrm{FS}}^2}$ is the mean-square voltage of a sinusoidal full-scale signal and $v_{\mathrm{N,eq,self}}$ is the equivalent rms ADC self-noise voltage Reference value: NA **SOURCE: Ainslie et al.** (2020)
system dynamic range **symbol**: $\Delta L_{\mathrm{DR,sys}}$	the quantity $\Delta L_{\mathrm{DR,sys}} = 10 \log_{10} \frac{\overline{v_{\mathrm{FS}}^2}}{v_{\mathrm{N,eq,self}}^2 + \overline{v_{\mathrm{N,self}}^2}}$ dB, where $\overline{v_{\mathrm{FS}}^2}$ is the mean-square voltage of a sinusoidal full-scale signal, $v_{\mathrm{N,eq,self}}$ is the equivalent rms ADC self-noise voltage and $v_{\mathrm{N,self}}$ is the non-acoustic self-noise voltage at the ADC input Reference value: NA **SOURCE**: ADEON (Ainslie et al., 2020)
Nyquist frequency **unit**: Hz	half the sampling rate **NOTES**: The Nyquist frequency is a property of the acquisition system. See also *Nyquist rate* (see Table A.2).
system-weighted sound pressure **symbol**: p_{sw} **unit**: Pa	weighted sound pressure when the linear filter is the receiving system **SOURCE**: ADEON (Ainslie et al., 2020) **NOTES**: The system-weighted sound pressure is the apparent sound pressure obtained by ignoring the frequency response of the acquisition system. I.e., by assuming the sensitivity of the system has the same (real) value at all frequencies.

Term	Definition
system-weighted sound pressure level **symbol**: $L_{p,\mathrm{sw}}$ **unit**: dB	level of the mean-square system-weighted sound pressure In equation form $L_{p,\mathrm{sw}} = 10\log_{10}\frac{\overline{p_{\mathrm{sw}}^2}}{p_0^2}$ dB where $\overline{p_{\mathrm{sw}}^2}$ is the mean-square system-weighted sound pressure **reference value**: $p_0^2 = 1\ \mu\mathrm{Pa}^2$ **SOURCE**: ADEON (Ainslie et al., 2020), corrected by deleting “in-beam”

Table A.5 Acoustical terminology related to system sensitivity. Source: ADEON terminology standard.

Term	Definition
free-field voltage sensitivity **synonym**: voltage sensitivity **symbol**: $M_{\mathrm{hp},v}$ **unit**: $\mathrm{V\ Pa^{-1}}$	ratio of the rms open-circuit output voltage to the rms spatially-averaged sound pressure in the undisturbed plane-progressive free field **NOTES**: Adapted from IEC (1994) (IEV 801-25-53). Free-field voltage sensitivity is a property of a voltage hydrophone, for a specified frequency band and a specified direction of sound incidence.
ADC sensitivity to voltage **symbol**: $M_{\mathrm{ADC},v}$ **unit**: $\mathrm{V^{-1}}$	ratio of rms digitized time signal ($n_{\mathrm{ADC,rms}}$) to rms ADC input voltage ($v_{\mathrm{ADC,rms}}$) In equation form $M_{\mathrm{ADC},v} = \frac{n_{\mathrm{ADC,rms}}}{v_{\mathrm{ADC,rms}}}$ **NOTES**: Unless the ADC input voltage is equal to zero, the ADC sensitivity to voltage is also equal to the ratio of the digitized time signal to ADC input voltage.
spectral system sensitivity **symbol**: $M(f)$ **unit**: $\mathrm{Pa^{-1}}$	ratio of digitized signal spectrum to sound pressure spectrum at the hydrophone In equation form $M(f) = \frac{N(f)}{P(f)}$, where $N(f)$ is the digitized signal spectrum, defined as the Fourier transform of the digitized time signal and $P(f)$ is the sound pressure spectrum
total system sensitivity **symbol**: M_{tot} **unit**: $\mathrm{Pa^{-1}}$	absolute value of the spectral system sensitivity, evaluated at a specified frequency **NOTES**: In principle the specified frequency is arbitrary. A well-designed acquisition system typically has a “flat” region on its calibration curve, within which the magnitude of the spectral system sensitivity is independent of frequency. In practice it is usual for the specified frequency to be in this flat region of the calibration curve. This choice ensures that for frequencies in this flat region the system-weighted sound pressure is approximately equal to the actual sound pressure.
equivalent rms hydrophone noise sound pressure **symbol**: $p_{\mathrm{N,eq,hp}}$ **unit**: Pa	ratio of the hydrophone’s rms open-circuit output noise voltage to the free-field voltage sensitivity **NOTES**: Adapted from ISO (2017), entry 3.6.1.15. Equivalent rms hydrophone noise sound pressure includes contributions from both acoustic and non-acoustic noise.
equivalent rms system noise sound pressure **symbol**: $p_{\mathrm{N,eq,sys}}$ **unit**: Pa	ratio of the rms integer ADC noise output to the total system sensitivity **NOTES**: Equivalent rms system noise sound pressure includes contributions from both acoustic and non-acoustic noise.

B Standard decidecade frequency bands

Standard bands are arranged logarithmically in frequency and are based on powers of ten around a center frequency of 1000 Hz. Multiplying this center frequency by integer powers of ten gives 10, 100, 1000 and 10 000 Hz. The band between each successive factor of 10 (e.g., from 100 to 1000 kHz) is a decade. The QSPs all use a finer resolution by dividing each decade band into ten equal sub-bands, each one tenth of a decade (i.e., one decidecade) wide. Table B.1, based on the ADEON Soundscape Specification (Ainslie et al., 2018), shows decidecade (ddec) bands according to IEC (2014), for decidecade frequency bands with center frequencies 10 Hz ($n = -20$) Hz to 100 kHz ($n = +20$). Each decidecade band in the table is identified by a unique integer index between $n = -20$ (10 Hz) and $+20$ (100 kHz), with $n = 0$ corresponding to 1 kHz. Center frequencies of nominal octave bands (the precise bandwidth of which is 3 ddec) are bold.

Table B.1 Decidecade frequency bands, as defined by IEC (2014), with center frequencies between 10 Hz ($n = -20$) and 100 kHz ($n = +20$). Band edge and center frequencies are stated to 5 significant figures.

Band index (n)	**Lower bound (f_{min}/Hz)**	**Center frequency (f_{C}/Hz)**	**Upper bound (f_{max}/Hz)**	**Nominal center frequency ($f_{\text{c,nom}}$)**
−20	8.9125	10.000	11.220	10 Hz
−19	11.220	12.589	14.125	12.5 Hz
−18	14.125	**15.849**	17.783	16 Hz
−17	17.783	19.953	22.387	20 Hz
−16	22.387	25.119	28.184	25 Hz
−15	28.184	**31.623**	35.481	32 Hz
−14	35.481	39.811	44.668	40 Hz
−13	44.668	50.119	56.234	50 Hz
−12	56.234	**63.096**	70.795	63 Hz
−11	70.795	79.433	89.125	80 Hz
−10	89.125	100.00	112.20	100 Hz
−9	112.20	**125.89**	141.25	125 Hz
−8	141.25	158.49	177.83	160 Hz
−7	177.83	199.53	223.87	200 Hz
−6	223.87	**251.19**	281.84	250 Hz
−5	281.84	316.23	354.81	320 Hz
−4	354.81	398.11	446.68	400 Hz
−3	446.68	**501.19**	562.34	500 Hz
−2	562.34	630.96	707.95	630 Hz
−1	707.95	794.33	891.25	800 Hz
0	891.25	**1000.0**	1122.0	1 kHz
1	1122.0	1258.9	1412.5	1.25 kHz
2	1412.5	1584.9	1778.3	1.6 kHz
3	1778.3	**1995.3**	2238.7	2 kHz
4	2238.7	2511.9	2818.4	2.5 kHz
5	2818.4	3162.3	3548.1	3.2 kHz
6	3548.1	**3981.1**	4466.8	4 kHz
7	4466.8	5011.9	5623.4	5 kHz
8	5623.4	6309.6	7079.5	6.3 kHz
9	7079.5	**7943.3**	8912.5	8 kHz
10	8912.5	10000	11220	10 kHz

Band index (n)	**Lower bound** ($f_{\min}/\mathrm{Hz}$)	**Center frequency** ($f_{\mathrm{C}}/\mathrm{Hz}$)	**Upper bound** ($f_{\max}/\mathrm{Hz}$)	**Nominal center frequency** ($f_{\mathrm{c,nom}}$)
11	11220	12589	14125	12.5 kHz
12	14125	**15845**	17783	16 kHz
13	17783	19953	22387	20 kHz
14	22387	25119	28184	25 kHz
15	28184	**31623**	35481	32 kHz
16	35481	39811	44668	40 kHz
17	44668	50119	56234	50 kHz
18	56234	**63096**	70795	63 kHz
19	70795	79433	89125	80 kHz
20	89125	100000	112200	100 kHz

A decidecade is approximately equal to one third of an octave, and for this reason is referred to by IEC (2014) as a “one-third octave” (Table B.2).

Table B.2 Fractional octave and fractional decade frequency bands.

Frequency ratio	**IEC 61260: 1995**	**IEC 61260-1: 2014**	**ISO 18405**	**ISO 80000-8**	**notes**
2	octave	-	octave	octave	
$2^{1/3}$	one-third octave	-	one-third octave one-third octave (base 2)		
10	-	-	decade	decade	
$10^{1/10}$	one-third octave	one-third octave	decidecade one-third octave (base 10)		an alternative name for this frequency ratio is “one-tenth decade” (ANSI S1.6-2016)