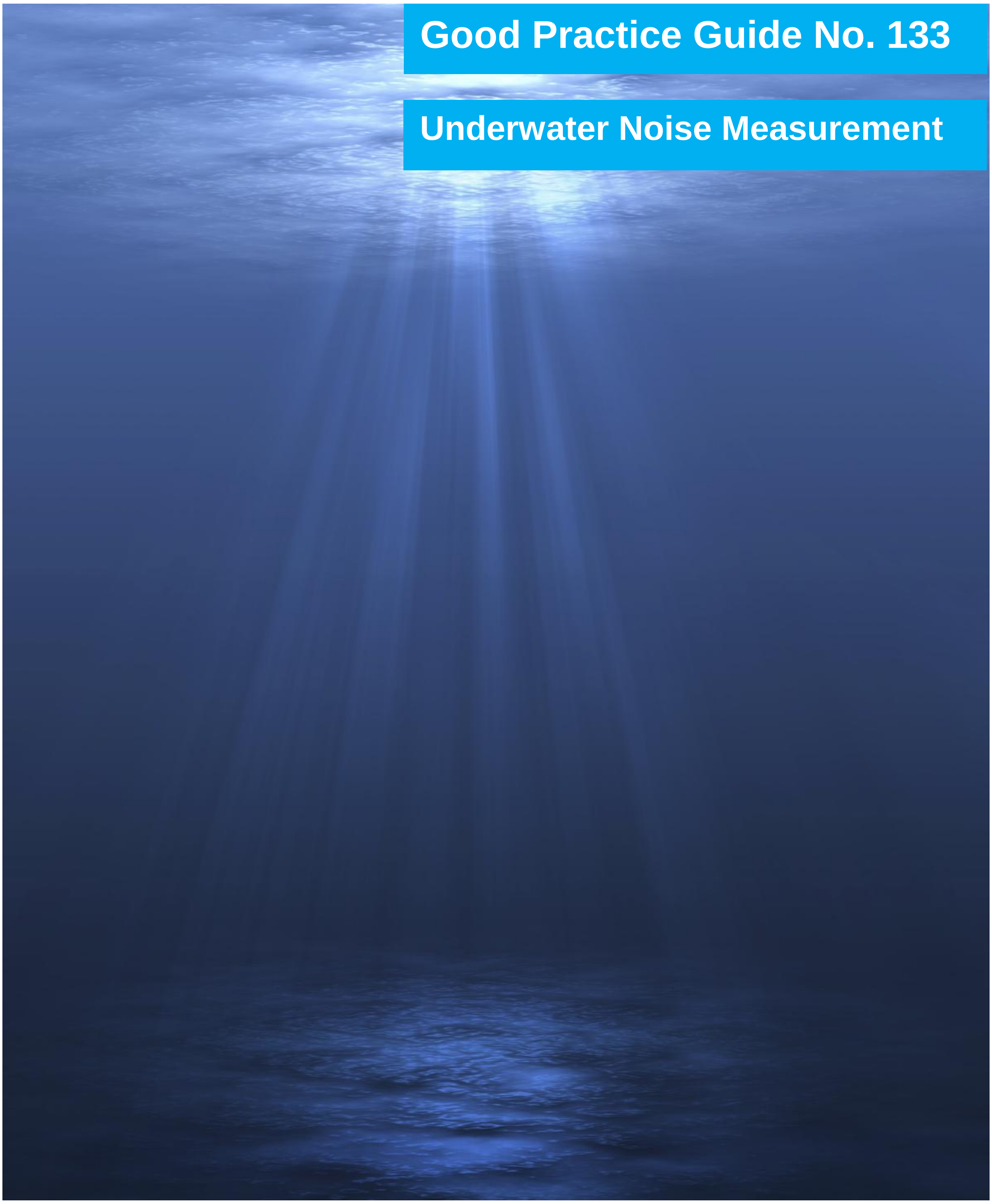
NPL National Physical Laboratory

Good Practice Guide No. 133

Underwater Noise Measurement



National Measurement System

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Good Practice Guide for Underwater Noise Measurement

Summary

This document provides guidance on best practice for *in-situ* measurement of underwater sound, for processing the data, and for reporting the measurements using appropriate metrics. Measured noise levels are sometimes difficult to compare because different measurement methodologies or acoustic metrics are used, and results can take on different meanings for each different application, leading to a risk of misunderstandings between scientists from different disciplines. Acoustic measurements are required for applications as diverse as acoustical oceanography, sonar, geophysical exploration, underwater communications, and offshore engineering. More recently, there has been an increased need to make *in-situ* measurements of underwater noise for the assessment of risk to marine life. Although not intended as a standard, these guidelines address the need for a common approach, and the desire to promote best practice.

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Authorship
This good practice guide was drafted by Stephen Robinson of the National Physical Laboratory with the assistance of Dr Paul Lepper (Loughborough University) and Dr Richard (Dick) Hazelwood (R&V Hazelwood Associates).

Document Review
Though the views in this good practice guide are those of the authors, the document was reviewed by a panel of UK acousticians before publication. This enabled a degree of consensus to be developed with regard to the contents, although complete unanimity of opinion is inevitably difficult to achieve. Note that the members of the review panel and their employing organisations have no liability for the contents of this good practice guide.

The Review Panel consisted of the following experts (listed in alphabetical order):

Dr Philippe Blondel	University of Bath
Mr Fabrizio Borsani	CEFAS
Mr John Burrows	QinetiQ Ltd
Dr Peter Dobbins	Ultra Electronics Ltd
Dr Richard (Dick) Hazelwood	R&V Hazelwood Associates
Professor Victor Humphrey	ISVR, University of Southampton
Dr Paul Lepper	Loughborough University
Mr Roland Rogers	National Oceanography Centre
Dr John Smith	DSTL
Dr Pete Theobald	NPL
Professor Peter Thorne	University of Liverpool
Mr Dick Wood	Bureau Veritas UK Ltd

The project Steering Committee consisted of representatives of Marine Scotland, The Crown Estate, DECC, JNCC, SNH, CEFAS and members of the Scottish Renewables (the representative body of the Scottish renewable energy industry).

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Future revisions
Revisions to this guide will be considered in December 2014. Any suggestions for additional material or modification to existing material are welcome, and should be communicated to Stephen Robinson, NPL (stephen.robinson@npl.co.uk).

Contents

1. Introduction

1.1 Background

There is an increasing need to measure and report levels of underwater sound in the ocean, partly driven by the need to conform to regulatory requirements with regard to assessment of the environmental impact of anthropogenic noise. Attempts to report measured noise levels are sometimes difficult to compare because different methodologies and acoustic metrics are used. These guidelines aim to provide guidance on good practice for *in-situ* measurement of underwater sound, for processing the resulting data, and for reporting the measurements using metrics that have agreed definitions.

Existing national and international standards for acoustics concentrate primarily on sound in air. They provide acousticians with a common language and enable unambiguous communication of scientific ideas and information about sound, and to provide guidance on how to measure sound. While the same need exists for underwater sound, there are relatively few comparable standards. Instead, the terminology and measurement methodologies are often passed on from scientist to scientist, and engineer to engineer.

In general, the measurement methods used in practice vary, and the metrics quoted can take on different meanings for each different application, leading to a risk of misunderstandings between scientists from different disciplines. Acoustic measurements are required for applications as diverse as acoustical oceanography, sonar performance assessment, geophysical exploration, underwater communications, and offshore engineering. More recently, there has been an increased need to make *in-situ* measurements of underwater noise for the assessment of risk to marine life.

1.2 Scope

The guidance in this document covers:

- identification of the common acoustic metrics for describing underwater noise, including definitions and units, and recommendations of how these metrics should be reported;
- choice of hydrophone and acquisition systems, including calibration requirements and quality assurance;
- deployment techniques, including vessel-based deployments and use of autonomous systems;
- techniques for measuring radiated noise;
- techniques for measuring ambient noise;
- guidance on spatial and temporal sampling;
- data handling and storage;
- data analysis, including metrics, integration periods, statistics, and requirements for auxiliary measurements and metadata;
- uncertainty evaluation.

1.3 Current international standards and recent developments

Considerable effort is currently being devoted to the topic of standardisation in international standards bodies. Mainly, this is taking place under the auspices of the International Organization for Standardisation (ISO), within ISO Technical Committee 43, Sub-Committee 3 (ISO TC43 SC3) which has the title “Underwater Acoustics”. There are currently three active working groups with the following remits:

WG1: Measurement of underwater sound from ships;
WG2: Underwater acoustical terminology;
WG3: Measurement of radiated noise from marine pile driving.

The work on measurement of ship noise is also undertaken in a joint working group with ISO TC8, which deals with shipping and maritime technology.

There is a mirror committee to ISO TC43 SC3 in the UK, which supplies the expertise from the UK acoustics community. This is run by the British Standards Institute (BSI), has the designation EH/1/7, and consists of expert underwater acousticians from academia, industry and government institutes.

The following standards have been published and are of relevance to the material in this report:

ANSI/ASA S12.64-2009/Part 1, 2009. *Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements*, American National Standard Institute, USA, 2009

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

IEC 1995 (EN 61260), *Electroacoustics - Octave-band and fractional-octave-band filters*, International Electrotechnical Commission, Geneva, Switzerland, 1996.

IEC60565: 2006 *Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz*, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006.

IEC 60050:1994, *International Electrotechnical Vocabulary, part 801: Acoustics and Electroacoustics*, (section 801-32 covers terms for underwater acoustics), International Electrotechnical Commission (IEC), Geneva, 1994.

ISO1996-1: 2006, *Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures*. International Organization for Standardization, Geneva, 2006.

ISO 80000-8: 2007. *Quantities and units – part 8: Acoustics*, International Organization for Standardisation, Geneva, 2007.

ISO/TR 25417:2007. *Acoustics — Definitions of basic quantities and terms*. International Organization for Standardisation (ISO), Geneva, 2007.

ISO/PAS 17208-1:2012 *Acoustics — Quantities and procedures for description and measurement of underwater sound from ships. Part 1: General requirements for measurements in deep water,* International Organization for Standardisation, Geneva, 2012.

JCGM 100:2008, Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurement (GUM), joint publication by BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2008. Available from www.bipm.org

The need for interim guidance

The timescale for the work of international standards committees is relatively slow because it incorporates input from many countries before consensus is reached. **The guidelines contained here are not intended as a standard** and will be superseded when national and international standards are published. Instead, they are intended to provide some interim guidance on good practice until such international standards are published. However, the contents have been informed by preliminary discussions that have taken place in the lead up to standards development.

Existing guidance documents (not international standards)

The work to develop new standards will build upon the expertise already gained by researchers in a number of countries who have been actively engaged in discussions on this topic for some time. It is these informal discussions that have led to the initiation of standardisation work within ISO. There are a number of existing guidance documents and protocols which have been influential in the emergence of the work on standardisation, and these documents have informed the guidelines provided here [TNO 2011a, TNO 2011b, Mueller and Zerbs 2011, Carter 2013]. In addition, the EU Technical Sub-Group on Noise (EU TSG Noise), an expert committee which was set up to provide guidance on the implementation of the EU Marine Strategy Framework Directive (MSFD), has produced recent reports which partly cover the topic of guidance on *in-situ* noise measurement [EU TSG 2014a, 2014b, 2014c].

Beneficiaries of the work

The beneficiaries of this work include consultants, offshore developers, oil and gas companies and developers of marine renewable energy; regulators wishing to base their requirements on a firm scientific foundation; and in general, all those making *in-situ* measurements of underwater sound. The guidance contained herein facilitates comparison between measurements of radiated noise from specific sources, including vessels and construction and operation of offshore structures for industries such as oil and gas and renewable energy developments.

1.4 Exclusions from the scope of these guidelines

Exposure metrics and impact assessment

The guidelines do **not** cover the choice or evaluation of impact criteria for injury or behavioural response of marine fauna. In this guide, no attempt is made to recommend any specific criteria for impact; nor is any attempt made to describe a methodology for evaluating exposure or impact metrics. These topics are covered in other publications in the scientific literature [Southall *et al* 2007, Nedwell *et al* 2007a, Oestman *et al* 2009, Ellison *et al* 2011, Finneran and Jenkins 2012, Halvorsen *et al* 2012, Thompson *et al* 2013].

The area of impact and exposure criteria is one that is rapidly evolving and new evidence is likely to be published in the next few years. Although much of the recent motivation for making *in-situ* measurements of underwater noise is for an assessment of environmental impact, the intention here is to separate out the acoustic part of the process from the assessment of impact. The guidance provided here does not prejudge the environmental assessment by making assumptions about the impact or exposure metrics used for the impact criteria. Instead, the guidance attempts to provide methods for determining the acoustic metrics needed for a range of impact criteria commonly applied at the moment.

Measurements of particle velocity and vibration

Many species are known to be sensitive to particle motion. For example, fish species and invertebrates are in general sensitive in this manner, with some also sensitive to sound pressure. In addition, some species that dwell on or close to the seabed may be affected by vibration of the seabed itself (for example, during offshore construction where marine pile driving is used). However, the guidelines in this document cover only the measurement of sound pressure in the water column.

The techniques and sensors for measuring vibration and particle velocity (in the water column or along the seabed) are currently relatively immature, and there is a lack of calibration standards. There is also a lack of knowledge of what levels of these parameters would cause an effect, and indeed little knowledge of what background levels exist in the ocean.

Note that the fact that particle motion is not covered in this guide should not be taken as an indication that it does not matter. In fact, it may well be highly significant, and its omission is merely a reflection that it is a little premature to attempt to provide definitive guidance at this point. However, as the technology and the knowledge base develops, future revisions of the guidelines may be expanded in scope to include guidance on measurements of particle velocity and seabed vibration.

Guidance on basic acoustics

This guide assumes a basic knowledge of acoustics or physics and does **not** attempt to provide a beginner's guide, nor a description from first principles. Readers wanting such guidance are referred to examples of good text books [Urick 1983, Kinsler *et al* 2000], and to several excellent web-sites:

US DOSITS web-site: www.dosits.org

US Marine Mammal Commission: www.mmc.gov/reports/workshop/pdf/sound_bklet.pdf

2. Metrics

2.1 Acoustic quantities

2.1.1 Introduction

The most important objective when stating the results of acoustic measurements is that the meaning be clear and unambiguous. If there is any scope for ambiguity, then the definitions for the terms used must be stated before they are first used. This rule is in some ways sufficient for most purposes, but for reasons of comparability, and since it is cumbersome to define each term every time it is used, some common definitions are needed for acoustic metrics. In this section, the quantities recommended for use in describing measurements of sound are defined.

Sound is a disturbance in pressure that propagates through a compressible medium (solid or fluid) and propagates via the action of elastic stresses involving local compression and expansion of the medium. A number of quantities may be used to describe a sound wave, but the most common is sound pressure. Sound pressure is often simply defined as the difference between instantaneous total pressure and the "equilibrium" pressure (the latter being that pressure which would exist in the absence of sound waves). Sound pressure is in general the most useful acoustical quantity in that it is relatively straightforward to measure, it is the quantity to which a hydrophone responds, and which the hearing organs of many species detect (though many marine species are sensitive to particle motion).

The unit of sound pressure is the pascal (Pa), which is equivalent to a newton per metre squared, or N/m^2, as defined by the International System of Units (S.I.) [BIPM 2006]. [1]

It should be noted that all attempts to measure sound are limited by the performance of the instrumentation. However, the *definitions* of quantities do not in themselves depend on the ability of instruments to measure them. All sensors and instruments have finite bandwidths and finite sizes that limit the ability to measure the sound field (creating bandwidth limitations, spatial averaging effects, etc). This does not alter the definition of the quantity – these effects are artefacts introduced during the measurement – but it does limit our ability to measure them.

2.1.2 Definitions of basic quantities and metrics

There are a number of different metrics that may be used as measures of the sound pressure [IEC60050 1994, IEC1995 1996, Morfey 2001, ISO1996-1 2006, ISO 80000-8 2007, ISO/TR25417 2007]. These are listed below, and some of them are illustrated graphically in Figure 2.1.

[1] Note that in this guide, the S.I. convention has been adopted [BIPM 2006]. Accordingly, S.I. units are used throughout. Accordingly, where the unit is named after a person, the symbol has an initial capital letter, but when written in full the unit is lower case (e.g. W and watts are used for the unit of power). Where compound units are formed, the convention chosen is to separate individual units by a raised dot (e.g. Pa·m).

sound pressure (or "instantaneous sound pressure")

The difference between instantaneous total pressure and pressure that would exist in the absence of sound. This is in effect the quantity that is being represented when a sound pressure waveform is plotted. Sound pressure is expressed in units of pascals (Pa).

peak sound pressure (or zero-to-peak sound pressure)

The maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure, and the unit is the pascal (Pa). This quantity is typically useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform.

peak compressional pressure

The maximum value of the magnitude of the compressional pressure during a stated time interval. Peak compressional pressure is expressed in pascals (Pa) and is sometimes referred to as "peak-positive sound pressure". A peak compressional pressure may only arise from a positive sound pressure. This quantity is typically most useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform.

peak rarefactional pressure

The maximum value of the magnitude of the rarefactional pressure during a stated time interval. Peak rarefactional pressure is expressed in pascals (Pa) and is sometimes referred to as "peak-negative sound pressure". A peak rarefactional pressure may only arise from a negative sound pressure, but is expressed as a positive valued quantity. This quantity is typically most useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform.

peak to peak sound pressure

The sum of the peak compressional pressure and the peak rarefactional pressure *during a stated time interval*. This quantity is typically most useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform. Peak-to-peak sound pressure is expressed in pascals (Pa).

root mean square (RMS) sound pressure

The square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specified time interval divided by the duration of the time interval. The RMS sound pressure is calculated by first squaring the values of sound pressure, averaging over the specified time interval, and then taking the square root. The RMS sound pressure is expressed in pascals (Pa). The averaging time must always be stated. The root mean square sound pressure, $\hat{p}$, may be expressed algebraically as:

$$\hat{p} = \left\{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p(t)^2 \mathrm{d}t\right\}^{\frac{1}{2}},$$

where p, is the sound pressure, and t_1 and t_2 are the start and stop times of the time interval over which the mean is evaluated.

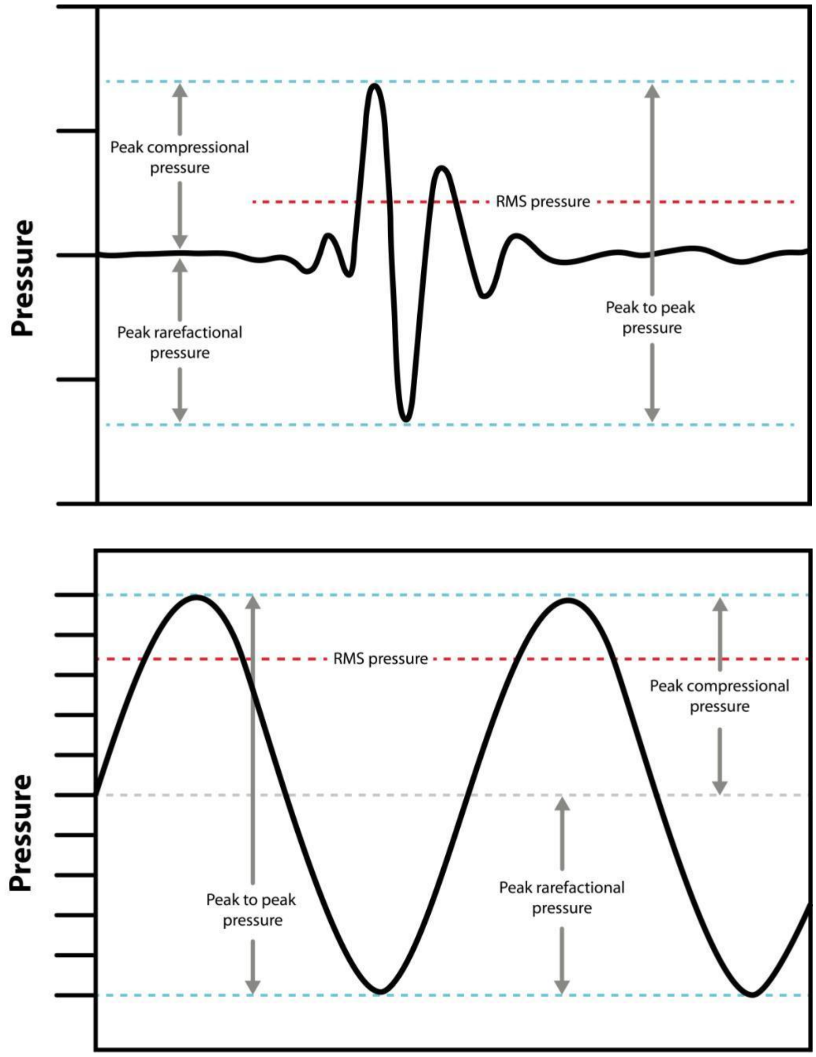

Fig 2.1: Some of the metrics for sound pressure illustrated for a sound pulse (upper plot) and for a periodic waveform (lower plot).

sound exposure

The integral of the square of the sound pressure over a stated time interval or event (such as an acoustic pulse). For a starting time t_1 and end time t_2, and sound pressure *p*, the sound exposure, *E*, is given by:

$$E = \int_{t_1}^{t_2} p^2(t)\,dt$$

Sound exposure is expressed in units of pascal squared seconds ($Pa^2 \cdot s$). As the integral of squared sound pressure over time, the quantity is sometimes called the “pressure-squared integral”. The quantity is sometimes taken as a proxy for the energy content of the sound wave (it may be converted to energy flux density by dividing by the specific acoustic impedance of the medium). When applied to an acoustic pulse, the integration time is the pulse duration. When applied to a single pulse (or event), the quantity is sometimes called “single pulse sound exposure” (or “single event sound exposure”). Note that the sound exposure useful as a measure of the exposure of a receptor to a sound field, and a frequency weighting is commonly applied. If a frequency weighting is applied, this should be indicated by appropriate subscripts.

cumulative sound exposure

The sound exposure determined for an extended period or sequence of pulses/events.

When stating the cumulative sound exposure, it is important to specify any other relevant information such number of pulses, total time duration, duty cycle of any sampling, etc. A more detailed discussion is provided in Section 2.3.

pulse duration (or signal duration)

The time during which a specified percentage of sound energy in the signal occurs. In the calculation, sound exposure may be used as a proxy for energy. The pulse duration is expressed in units of seconds (s).

A typical value of the percentage taken is 90, so that the duration is the time window during which 90% of the energy is present. This metric is intended for use to describe pulsed signals. If the percentage is represented by *X*, the metric is typically calculated by starting at (50-*X*/2)% and ending at (50+*X*/2)% of total energy (or 5% to 95% when X = 90).

Note that this definition covers only *X*% of the overall pulse; if it is necessary to account for all time (or energy) in the pulse (including the "missing" 10% in the example given), multiply the above value by 100/*X*.

pulse repetition frequency (pulse repetition rate)

The number of pulses or events arriving per second, expressed in units of hertz (Hz). Note that this is not the same as the number of cycles of signal arriving per second (the acoustic frequency).

spectral density

Any quantity expressed as a contribution per unit of bandwidth.

An example is sound exposure spectral density, expressed in units of $Pa^2 \cdot s/Hz$.

sound particle displacement (acoustic particle displacement)

The instantaneous displacement in a stated direction of a particle in a medium from its position in the absence of sound waves. The sound particle displacement is expressed in units of metres (m).

sound particle velocity (acoustic particle velocity)

The instantaneous velocity of a material particle in a stated direction due to the action of sound waves, expressed in units of metres per second (m/s). The sound particle velocity is equal to the rate of change with time of the acoustic particle displacement in a stated direction.

sound particle acceleration (acoustic particle acceleration)

The instantaneous acceleration of a material particle in a stated direction due to the action of sound waves, expressed in units of metres per second squared (m/s^2).

mean square sound pressure

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

sound intensity (instantaneous)

The product of the sound pressure and the particle velocity at a point in the sound field. Expressed in units of watts per metre squared (W/m^2). Sound intensity is a vector quantity and is expressed for a specific direction.

time-averaged sound intensity

The time-average of the sound intensity over a stated time interval in a stated direction. Expressed in units of watts per metre squared (W/m^2), it is a vector quantity and is expressed for a specific direction.

sound energy flux density

The time-integrated sound intensity at a far-field measurement position in a stated direction. Expressed in units of joules per squared metres (J/m^2).

sound energy

The energy contained in a sound wave in a specified time duration. For an acoustic pulse, it is the total energy contained in the pulse when radiated by the source, and is equal to the spatial integral of the sound energy flux density over all directions. The unit is the joule (J).

sound power

The sound power is the sound intensity integrated over a closed surface surrounding a source. It is the rate of sound energy radiated by a source. It is expressed in units of watts (W).

source factor

The source factor is the product of the far-field acoustic pressure and the distance from the source in a stated direction in the acoustic far-field. It is expressed in units of Pa·m.

rise time (of an acoustic pulse)

The time required for the sound pressure to rise from *X*% to *Y*% of its maximum value, with 5% and 95% typically chosen for values of *X* and *Y* respectively. The unit is the second (s).

third-octave frequency band

A frequency band whose bandwidth is one third of an octave, where an octave represents a doubling in frequency. One third of an octave is a frequency ratio corresponding to a ratio of $2^{1/3} \approx 1.2599$.

Note that there is an alternative expression for "third octave" as 1 deci-decade which is also permitted by IEC 61260:1995. The interval of a deci-decade is defined as one tenth of a decade or $10^{0.1} \approx 1.2589$, which is smaller than one third of an octave by 0.08%.

Third-octave bands originate from studies on human hearing and the extent to which noise at one frequency can interfere with hearing at another. Studies show that these "critical bands" are close to third-octave bands over much of the human hearing range (though other species may have different critical bands).

frequency weighting

Frequency-dependent normalised factor(s) by which spectral components are multiplied, resulting in the modification (usually reduction) of the amplitude of some components. The frequency weighting may comprise a set of factors by which discrete frequency components are multiplied, or a continuous frequency-dependent function. Essentially, frequency weighting is analogous to a filtering operation applied in the frequency domain. Frequency weightings are normalised factors and have no units or dimensions, but are sometimes expressed as relative factors in decibels (with no reference value).

The main motivation for applying a frequency weighting is to account for the frequency-dependent sensitivity of a receptor. Most often, the receptor is either a specific marine species or a category of species, and the weighting is then known as an "auditory weighting function". This is analogous to the weighting functions used to represent human hearing such as "A-weighting" and "C-weighting" (in this case the different weightings are used for different levels of sound). For a specific marine species, an auditory weighting function may be derived by inversion and normalisation of the hearing response of the species being studied, either using the hearing threshold [Nedwell *et al* 2007a] or by use of equal loudness contours [Finneran and Schlundt 2011]. Alternatively, a generic auditory weighting function may be used to represent a class or category of species (for example, "mid-frequency cetaceans") [Southall *et al* 2007]. Note that different frequency weightings may be appropriate for different types of sound exposure.

2.2 Levels in decibels

2.2.1 Use of decibels

In acoustics, it is common to express certain of the above quantities as levels using decibels (dB). A level is a method of expressing the magnitude of a quantity as a logarithmic ratio to a reference value. The decibel uses logarithms to base 10. The decibel is itself not an S.I. unit, but it has been accepted by the Committee International des Poids et Measures for use with the S.I.

All absolute levels expressed in decibels are expressed relative to a reference value of that quantity. The basic convention for calculating levels in decibels is as follows:

$$Level\ of\ quantity\ A = 10\ \log_{10}\left[\frac{A}{A_0}\right]$$

where A is the value of the quantity and A_0 is the reference value of that quantity (both the values are expressed in the same units, thus rendering the ratio dimensionless). Note that the use of 10 as the multiplier makes the units into **deci**bels, or one-tenth of a bel (the bel being an inconveniently large unit for many applications).

The convention for the use of decibels is that the above ratio is taken of quantities that relate to power (or energy) of a signal. When using decibels for quantities which depend on the square root of the signal power or energy (sometimes called "field quantities"), it is common to make use of the following mathematical relationship in the expression of the level in decibels:

$$Level\ of\ quantity\ B = 10\ \log_{10}\left[\frac{B^2}{B_0^2}\right] = 20\ \log_{10}\left[\frac{B}{B_0}\right]$$

where B is the value of the field quantity and B_0 is the reference value of that quantity. Examples of field quantities where the above mathematical identity is commonly used are *sound pressure*, and *electrical voltage*.

When reporting absolute values of acoustic levels in decibels, it is strongly recommended that the following principles be adopted:

- State the physical parameter clearly
- State the reference value clearly, preferably in S.I. units
- State any averaging time clearly
- State any applicable frequency bandwidth clearly
- State any frequency weighting clearly

Relative differences expressed in decibels

Note that decibels are sometimes used to describe *relative differences* or changes in value of a quantity. Examples of this usage include use for expression of gains and losses, and in such cases the reference value is *not* required because what is being expressed is a gain or loss *factor* (in essence, the reference value is unity and so is omitted). Specific examples include the gain of amplifiers and the loss in signal when transmitted or reflected at a medium boundary. Here, decibels are used without a reference level; for example: "the amplifier voltage gain was set to 40 dB" for an amplifier which amplifies the electrical voltage by a factor of 100.

2.2.2 Acoustic quantities expressed as levels

sound pressure level (SPL)

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

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

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

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

$$SPL = 10\ \log_{10}\left[\frac{\hat{p}^2}{p_0^2}\right] = 20\ \log_{10}\left[\frac{\hat{p}}{p_0}\right]$$

where $\hat{p}$ is the root mean square sound pressure described in Section 2.1, and p_0 is the reference value of the sound pressure. Note that the reference value of SPL for sound in water is one micropascal (1 μPa), leading to SPL being expressed in units of decibels *relative to* 1 μPa, or alternatively **dB re 1 μPa**.

Note that the time interval used in the calculation of SPL must be stated. Any frequency weighting applied must be stated (and defined).

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

sound exposure level (SEL)

The sound exposure level (SEL) is calculated from ten times the logarithm to the base 10 of the ratio of the sound exposure, *E*, to a reference value, E_0.

$$SEL = 10\ \log_{10}\left[\frac{E}{E_0}\right]$$

The reference value for sound exposure level is 1 μPa^{2}s.

Note that the integration time must be specified. When applied to an acoustic pulse, the integration time is the pulse duration. If a specific frequency weighting is applied, this should be stated or indicated by appropriate subscripts. The quantity is sometimes taken as a proxy for the energy content of the sound wave. Note that the sound exposure useful as a measure of the exposure of a receptor to a sound field, and a frequency weighting is commonly applied. If a frequency weighting is applied, this should be indicated by appropriate subscripts.

When applied to a single event, the quantity is commonly called the "single event sound exposure level" (or "single pulse sound exposure level").

cumulative sound exposure level

The total sound exposure level determined for an extended period or sequence of pulses/events.

When stating the cumulative sound exposure level, it is important to specify any other relevant information such number of pulses, total time duration, duty cycle of any sampling, etc. A more detailed discussion is provided in Section 2.3.

peak sound pressure level (or zero-to-peak sound pressure level)

Peak sound pressure level is equal to twenty times the logarithm to the base 10 of the ratio of the peak sound pressure, p_{peak}, to the reference value, p_0:

$$L_{peak} = 20\ \log_{10}\left[\frac{p_{peak}}{p_0}\right]$$

where the reference value is 1 μPa. If a specific frequency weighting is applied, this should be defined and indicated by appropriate subscripts.

It is recommended that peak sound pressure level not be abbreviated to "peak SPL". Since SPL generally refers to a time-averaged quantity, the meaning is ambiguous - it could be interpreted at "peak sound pressure expressed as a level", or as the "peak (or maximum) of the SPL".

peak to peak sound pressure level

Peak-to-peak sound pressure level, L_{pp}, is equal to twenty times the logarithm to the base 10 of the ratio of the peak-to-peak sound pressure, p_{pp}, to the reference value, p_0:

$$L_{pp} = 20 \ \log_{10} \left[\frac{p_{pp}}{p_0} \right]$$

where the reference value is 1 µPa. If a specific frequency weighting is applied, this should be defined and indicated by appropriate subscripts.

peak compressional pressure level

Peak compressional sound pressure level is equal to twenty times the logarithm to the base 10 of the ratio of the peak compressional sound pressure to the reference value, where the reference value is 1 µPa. If a specific frequency weighting is applied, this should be defined and indicated by appropriate subscripts.

peak rarefactional pressure level

Peak rarefactional sound pressure level is equal to twenty times the logarithm to the base 10 of the ratio of the peak rarefactional sound pressure to the reference value, where the reference value is 1 µPa. If a specific frequency weighting is applied, this should be defined and indicated by use of appropriate subscripts.

received level

This is a somewhat imprecise term meaning the level of an acoustic quantity at a specific spatial position within an acoustic field, usually the position of a marine receptor (which could be a hydrophone or an animal). Note that the position should be stated along with the value (for example, in terms of the distance from the acoustic source, depth in the water column, etc). The term "received level" could refer to any of the above quantities expressed as levels, and is sometimes useful as shorthand (especially when drawing a distinction with Source Level). However, because of the potential ambiguity, it is recommended that one of the above specific level quantities is used instead of received level, depending on the actual quantity being described.

spectral density level

Ten times the logarithm to the base 10 of the ratio of the spectral density of a quantity per unit bandwidth, to a reference value.

An example is the mean-square sound-pressure spectral density, which is expressed in units of dB re 1 µPa^2/Hz.

source level

The source level is equal to twenty times the logarithm to the base 10 of the product of the far-field sound pressure and the distance from the source in a specified direction. It is expressed in units of dB re 1 µPa·m, but in practice the unit is far more commonly seen expressed as dB re 1 µPa at 1m (understood as dB re 1 µPa *referred to* 1m).

The source level is a measure of the acoustic output of a source, and may be considered as a characteristic property of the source itself, independent of the propagation path from source to receiver position. It is calculated by measuring the SPL in the acoustic far-field of the source, in a specified direction, and propagating the value back to the reference distance of 1 m from the acoustic centre of the source using an appropriate propagation model. Note the relationship of source level to source factor (see section 2.1.2).

The source level is most commonly calculated using the sound pressure level (SPL). However, on occasion it is calculated using the peak pressure, in which case it is known as the peak pressure source level.

See section 6.2.3 for more details on source level.

energy source level

The energy source level is equal to ten times the logarithm to the base 10 of the product of the far-field sound exposure and the squared distance from the source in a specified direction. It is expressed in units of dB re 1 $\mu Pa^2 \cdot m^2 \cdot s$.

The energy source level may be used as a proxy for the acoustic energy output of a source, and is a characteristic property of the source itself, independent of the propagation path from source to receiver position. It is calculated by measuring the SEL in the acoustic far-field of the source, in a specified direction, and propagating the value back to the reference distance of 1 m from the acoustic centre of the source using an appropriate propagation model.

See section 6.2.3 for more details on energy source level.

sound power level

The level of the sound power, calculated as ten times the logarithm to the base 10 of the sound power (the power being the rate of sound energy radiated by a source). It is expressed in decibels relative to a stated reference level, most often a value of 1 picowatt, making the units dB re 1 pW. This term is commonly used is air acoustics to describe the acoustic output of a source, but is less common in underwater acoustics (where source level is more common).

2.3 Recommended metrics for reporting underwater sound

2.3.1 Pulsed (impulsive) sounds

Impulsive or pulsed sounds are characterised by short bursts of acoustic energy of finite duration. These are sometimes referred to as transient sounds. Examples of pulsed sound are produced by marine pile driving, explosions, and airgun sources.

From the metrics discussed in Section 2.2, the most appropriate metrics for use with pulsed sounds are:

- Sound Exposure Level (SEL) for both single pulse and cumulative (for a series of pulses);
- Peak sound pressure level;
- Peak-to-peak sound pressure level;

It may also be useful to calculate the peak compressional sound pressure level and peak rarefactional sound pressure level, the pulse duration, and the pulse repetition frequency.

Strictly, the use of decibels for peak levels of pulsed waveforms is somewhat controversial because decibels were originally used only for quantities which may be related to the time-averaged power. However, the usage has now become common practice.

The SEL may be considered as a proxy for a measure of the pulse energy content. Note that for a plane-wave in a free-field environment (an unbounded medium), the sound exposure in $\mu Pa^2 \cdot s$ can be converted to units of energy flux density in J/m^2 by dividing by the specific acoustic impedance of the medium (the specific acoustic impedance being the product of medium density and sound speed in the medium). When expressed in decibel notation, this means that 0 dB re 1 J/m^2 is equivalent to 182 dB re 1 $\mu Pa^2 \cdot s$ in typical sea water.

For an acoustic pulse, the SEL is calculated over the pulse duration, which is commonly defined as the time occupied by the central portion of the pulse, where 90% of the pulse energy resides. This is useful because it can be difficult to determine the exact start of the pulse when the waveform contains noise. Figure 2.2 shows the calculation of SEL using the definitions of Section 2.2 over the duration of a pulse measured while monitoring a marine pile driving operation. For the 100% value of the pulse SEL, it would be necessary to add 0.45 dB to the 90% value.

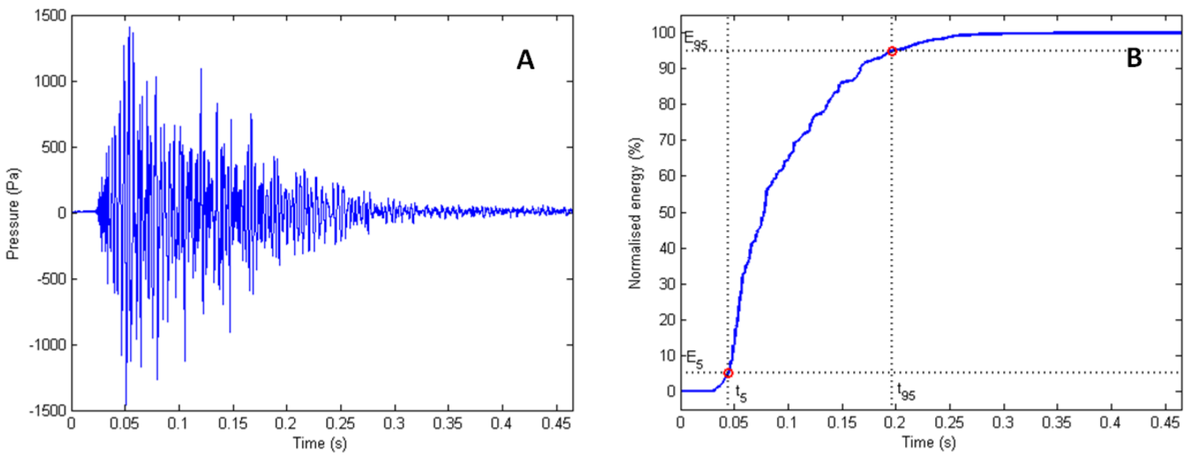

Fig 2.2: Example of pulsed waveform taken from a measurement of marine pile driving (A); and calculation of pulse duration over pulse (B).

The SEL for each impulsive noise event can also be aggregated by summation to calculate the total SEL (or SEL dose) for the purposes of environmental impact assessment over an entire sequence of pulses, or over an extended time duration [Madsen 2005, Southall *et al*. 2007].

2.3.2 Continuous sounds

Continuous sounds are sounds where the acoustic energy is spread over a significant time, typically many seconds, minutes or even hours. The amplitude of the sound may vary throughout the duration, but the amplitude does not fall to zero for any significant time. The sound may contain broadband noise and tonal (narrowband) noise at specific frequencies. Examples of continuous sound include ship noise, operational noise from machinery including marine renewable energy devices, and noise from drilling.

The metric most suitable for continuous sounds is Sound Pressure Level (SPL). Note that by convention, this is a time-averaged quantity and is most commonly understood as an RMS value. The averaging time used in the calculation of the values of SPL must be stated.

A SEL metric can also be used for continuous noise sources. In this case, the sound exposure level across a frequency band is integrated across a fixed time period rather than over individual events or pulses. A period of 1 second is sometimes used for the duration [Southall *et al* 2007]. As with assessment of SEL from impulsive sources, the SEL can be aggregated by summation to calculate the total SEL across a longer exposure period.

Summary: Acoustic Metrics

The most appropriate metrics for use with **pulsed sounds** are:

- Single pulse Sound Exposure Level (SEL)
- Cumulative Sound Exposure Level (SEL) (for a series of pulses);
- Peak sound pressure level;
- Peak-to-peak sound pressure level.

It may also be useful to calculate the peak compressional sound pressure level and peak rarefactional sound pressure level, the pulse duration, and the pulse repetition frequency.

The metric most suitable for **continuous sounds** (including ambient noise) is:

- Sound Pressure Level (SPL).

Note that by convention, this is a time-averaged quantity and is most commonly understood as an RMS value. The averaging time used in the calculation of the values of SPL must be stated.

Where continuous sounds also contain transient or pulsed sounds from specific events, the metrics used for pulsed sounds should be used to describe these specific events.

3. Measuring instrumentation

This section deals with the choice of measuring instrumentation and the key performance specifications, including hydrophone and measuring instrumentation, system calibration, data quality assurance and storage.

3.1 System performance

3.1.1 Sensitivity

Ideally, the sensitivity of the hydrophone and measuring system should be chosen to be an appropriate value for the amplitude of the sound being measured. The aim in the choice of the system sensitivity is to:

- avoid poor signal-to-noise ratio for low amplitude signals;
- avoid nonlinearity, clipping and system saturation for high amplitude signals.

Thus, for measurement of low amplitude signals (for example, ambient noise in a quiet location), a high sensitivity system is preferable. However, for measuring high amplitude signals (for example, at close range to a source of high output level), a lower sensitivity is preferable to avoid saturating the measurement system. It is difficult to choose the sensitivity of the measuring system without some advance knowledge of the amplitude of sound likely to be measured. To build in some flexibility, it is preferable to have some selectable gain in the amplification stages, or in the settings of the Analogue to Digital Converter (ADC). These can then be set to appropriate values once the sound levels are known after some initial measurements. However, it should be remembered that for hydrophones which have integral preamplifiers (this is often the case for low-noise high sensitivity hydrophones), the integral preamplifier gain cannot usually be modified, and such hydrophones may not be appropriate for high amplitude signals.

The sensitivity of the entire measuring system must be known if absolute measurements of the sound field are required, and this will require a calibration (see Section 3.2). This includes the sensitivity of hydrophones and the gain of any amplifiers, filters and ADC's present in the instrument chain. The sensitivity is described in terms of the electrical voltage developed per pascal of acoustic pressure, and is stated in units of V/Pa (or, using units more appropriate for a typical sensitivity magnitude, in µV/Pa). The sensitivity level is often expressed in decibels as dB re 1 V/µPa. Note that the choice of a 1 V/µPa as the reference value leads to hydrophone sensitivity levels having very large negative values (for example: 56 µV/Pa is equivalent to -205 dB re 1 V/µPa).

Where the system records the sound as a digital waveform (rather than providing an analogue voltage), the sensitivity may be expressed in digital counts per pascal. Note that the range of numeric values produced by an ADC relate to the number of bits used in the conversion, the full voltage range allowed for the analogue signal being represented by values covering a range equal to 2^N where N is the number of bits of the ADC. For example, a 16 bit ADC represents the full scale voltage range with 2^{16} values (65,536 values).

3.1.2 Frequency response

The frequency response of the measuring system is the sensitivity as a function of acoustic frequency, and it is desirable for this response to extend to a high enough frequency to faithfully record all frequency components of interest within the measured signals. This requires that the hydrophone, and any amplifier and filter, be sufficiently broadband. The maximum frequency of interest will depend upon the motivation for the measurement; one example might be the maximum frequency of hearing of relevant marine receptors; alternatively, it may be the maximum frequency radiated by a specific source (though without first measuring the source, this may not be known).

The requirement for unambiguous representation of the signals within the desired frequency range requires the sampling frequency of any ADC within the recording system to be greater than two times the maximum acoustic frequency in the signal to be recorded (this is commonly known as the Nyquist frequency). It is common for systems to oversample such that the sampling frequency exceeds the minimum required (it is rare for systems to offer full frequency coverage up to the Nyquist frequency). It is advisable to use an anti-aliasing filter to avoid ambiguous representation of frequency content. Where the measured data are to be represented in third-octave bands, the maximum frequency of interest will be the upper limit of the maximum third-octave frequency band of interest.

It is desirable that the system sensitivity be invariant with frequency over the frequency band of interest (ie that it possess a “flat response”). Any significant resonance behaviour within the frequency range of interest will tend to distort the recorded data, causing amplification of frequency components close to the resonance frequency and potentially distorting the time waveform for any broadband pulses. In practice, it is difficult to achieve a perfectly flat response at high kilohertz frequencies because of variations in the hydrophone response, for example due to resonance(s). It is desirable to select a hydrophone with a resonance frequency outside of the frequency range of interest, or as high as reasonably possible within that frequency range. However, there will be a trade-off between frequency response and sensitivity because hydrophones with a high resonance frequency tend to be physically small and relatively insensitive.

At low frequencies, the hydrophone response will roll-off at a frequency governed by the electrical capacitance and leakage resistance. For piezoelectric hydrophone elements, this frequency can be very low indeed (<<1 Hz); however, a hydrophone that is damaged (for example, one that has incurred water ingress) can exhibit a roll-off at much higher frequencies due to the consequent reduction in the leakage resistance. Some commercial hydrophones with integral preamplifiers are designed with a high pass filter to cut out frequencies of less than about 10 Hz to reduce the influence of very low frequency parasitic signals generated by non-acoustic mechanisms such as surface wave motion. The use of such a filter is desirable if measurements are to be made from surface platforms in moderate to severe sea-states. However, note that low frequency acoustic signals will be attenuated by the action of the filter.

Note that it is possible to correct for the variation in the sensitivity with frequency if the hydrophone is calibrated over the full frequency range of interest [IEC 60565 2006].

3.1.3 Directivity

Ideally, a hydrophone would have an omnidirectional response such that its sensitivity is invariant with the direction of the incoming sound wave. In such cases, the orientation of the hydrophone during measurements would be unimportant. However, omnidirectionality is only an approximation valid at low frequencies where the hydrophone size is a small fraction of the acoustic wavelength. When the hydrophone size is comparable to or greater than the acoustic wavelength at the frequency of interest, the hydrophone will exhibit a response that shows appreciable directionality.

In this case, it is possible for the measurements to underestimate the sound pressure if the hydrophone is not oriented such that the principal axis (the axis for which the hydrophone has been calibrated) is aligned with the direction of the incoming sound wave [IEC 60565 2006, ANSI S1.20 2012]. The hydrophone directionality will first manifest itself along the direction of the hydrophone body and cable due to shielding of the hydrophone element by the body/cable, so measurement of radiated noise from a source should not be made with the source aligned with this direction (do not point the hydrophone away from the source with the body and cable shielding the element).

In practice, for typical measuring hydrophones, this becomes a significant issue only at high tens of kilohertz (or even hundreds of kilohertz), and the problem may be minimised by use of small high frequency hydrophones (though it should be noted that such hydrophones may have low sensitivity).

One issue that can cause enhanced directionality is where the hydrophone is deployed close to another structure that is capable of reflecting the sound waves. The combination of the direct and reflected waves causes interference, the nature of which will change depending on the arrival angle for the sound wave. This effect may be evident at kilohertz frequencies if the hydrophone is deployed close to a support structure such as a heavy mooring or support, or a recorder case that houses electronics and batteries but is mostly air-filled. This configuration should be avoided if an omnidirectional response is required at kilohertz frequencies. Similarly, if the hydrophone has a guard deployed around it (a protective cage to prevent damage of the element by impact), this may influence the directivity at kilohertz frequencies and should be avoided if an omnidirectional response is required (or the effect should be quantified by directional response measurements).

There are some situations where it is advantageous for the hydrophone to exhibit some directionality in sensitivity, for example in order to determine the direction of the incoming signals or to discriminate against self-noise from a deployment platform (such as a noisy vessel). This is usually accomplished by use of more than one hydrophone to form an array, or by use of a baffle or shield to reduce the sensitivity in a given direction (for example, from the surface). In these situations, the hydrophone or array directivity must be known from measurements.

3.1.4 System Self-Noise

The system self-noise of the measuring system (sometimes termed the “noise floor”) is a crucial parameter when measuring low levels of sound, and governs the minimum sound pressure that may be measured by the system.

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

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

In the context considered here, the system self-noise is considered to be the noise originating from the hydrophone and recording system (for considerations of deployment and platform noise, and how to minimise it, see Section 4.3). The system self-noise is the noise generated by the system *in the absence of any signal due to an external acoustic stimulus*. This noise is electrical in nature, and is generated by the hydrophone itself and any electronic components such as amplifiers and ADCs. This is normally expressed as a noise-equivalent sound pressure level in dB re 1 $\mu Pa^2/Hz$ [IEC 60565, 2006, ANSI S1.20 2012]. The system self-noise varies with frequency and as a result is typically presented as a noise spectral density level versus frequency.

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

To achieve acceptable signal-to-noise ratio when measuring acoustic signals, the self-noise equivalent sound pressure level should ideally be at least 6 dB below the lowest noise level to be measured in the frequency range of interest. It is common to compare values for system self-noise with classic empirical curves for ambient noise levels in the ocean, such as those of Wenz [Wenz 1962] and Knudsen [Knudsen 1948].

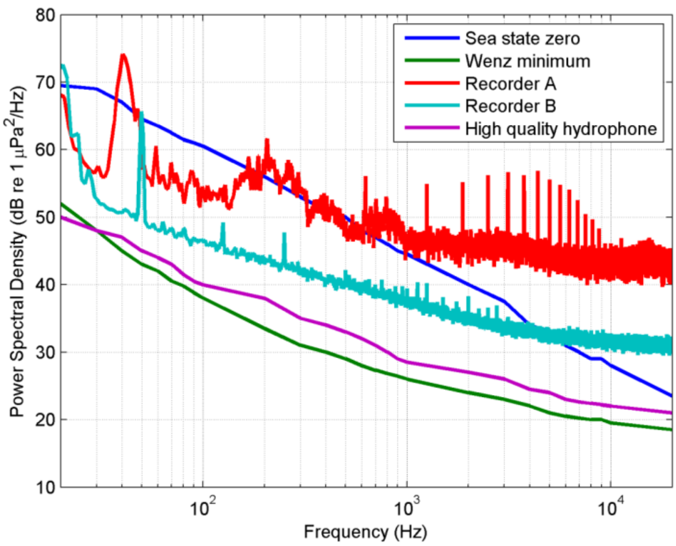

Fig 3.1: System self-noise for three measurement systems compared to sea state zero and Wenz minimum levels. Recorder A and B are less suitable for very low noise applications, but may be quite suited for applications where the signal amplitude substantially exceeds the noise floor.

Fig 3.1 shows these curves along with measured system self-noise data for a high-quality low-noise hydrophone, and two other recording systems (all measured data are for commercially available systems). The high-quality hydrophone has been designed to optimise the noise performance, and the self-noise of such a system will typically be better than sea-state zero and can even approach Wenz's lowest ocean noise levels. Systems where the self-noise is not one of the key design parameters (recording systems A and B in Figure 3.1) are likely to have a higher noise floor.

When measuring high amplitude sound, for example close to a sound source, the self-noise performance is not a key performance parameter and the requirement can be relaxed.

3.1.5 Dynamic range

The dynamic range of the measuring system is the amplitude range over which the system can faithfully measure the sound pressure. This ranges from the noise floor of the system (which defines the lowest measurable signal) to the highest amplitude of signal that may be measured without significant distortion. The system dynamic range should be chosen to be sufficient to enable the highest expected sound pressure to be recorded faithfully without distortion or saturation caused by the hydrophone, amplifier and ADC.

High amplitude sounds which are well beyond the maximum measurement capability of the measuring system will cause clear and obvious distortions in the measured data. For example, clipping may occur where the peaks of the signal are missing from the data (the peaks being truncated at the full-scale value of the system ADC). A very high amplitude signal can cause the amplifier electronics to saturate, an effect from which the system can take some time to recover.

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

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

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

Another issue that may cause difficulty when measuring broadband signals is that the amplitudes of the frequency components can vary over several orders of magnitude. For example, this can be a problem when measuring ambient noise where the low frequency components (eg at a few hundred hertz) may be much higher amplitude than the high frequency components (at tens of kilohertz). One method to overcome this problem is to use a measuring system which consists of several channels, each of which is used to measure a specific frequency band [Lammers *et al* 2008]. For each of the frequency bands, the amplifier gain setting, the ADC scale setting and even the hydrophone can be chosen to match the expected sound pressure levels and achieve good quality data that are significantly in excess of the noise floor but without distortion or saturation. The frequency bands must overlap if a continuous spectrum is to be recorded. A disadvantage of this approach is that the system is far more complex, requires more calibration, and requires processing such that the data for each frequency band are combined to form an overall spectrum. In addition, if two hydrophones are used, it is not possible to co-locate them, which means that the acoustic field will be sampled in two different positions (potentially important at high frequencies).

3.1.6 Potential issues with autonomous recorders

Autonomous recorders for use in measuring underwater sound are now increasingly available commercially. Such recorders consist of a hydrophone connected to an electronics pod containing amplifier, ADC, data storage media and batteries to power the unit. These devices have greatly increased the capability for ocean noise measurement without the need for bespoke designs that require great expertise to set up and operate. The issues raised in the earlier sections are also relevant to the use of these devices, but there are also a few specific issues that are worthy of note [EU TSG 2014b].

The performance of the autonomous recorder must be appropriate for the application so that the device is “fit-for-purpose”. Some designs have been adapted from equipment designed to perform other tasks, and may not be well suited for use in making absolute measurements of sound. Users should ensure that the equipment performance meets the needs of the measurement requirement, and make specific requests of suppliers with regard to performance. Key performance parameters include:

Calibration: The recorder should be supplied with a full system calibration including all information required to determine the absolute levels of the measured data (including hydrophone calibration, amplifier gains, ADC scale factors, etc). If not supplied by the manufacturer, a traceable calibration should be obtained from an accredited independent source, rather than relying on nominal figures from manufacturer’s specification. An *in-situ* calibration check with a hydrophone calibrator (pistonphone) is strongly recommended before and after deployment. This will cause a signal of known sound pressure level to be recorded within the stored data file, and will provide valuable information on the system performance (at least at one frequency).

Self-noise: For measurement of low amplitude signals, the system self-noise is a key parameter and this information should be requested from the supplier. High self-noise can originate from poor choice of hydrophone and amplifiers, or from pick-up of electrical noise generated by the electronics and data storage system (the latter can sometimes generate electrical spikes which are recorded as spurious signals). The electronics pod can also display resonance behaviour at very low frequencies, and this can affect the overall sensitivity if the hydrophone is connected rigidly to the recorder pod.

Influence of recorder body (and guard): The proximity of the hydrophone to the body of the recorder unit (which is usually an air-filled case containing the batteries and electronics) can give rise to problems from reflected signals scattered from the recorder body being picked up by the hydrophone. The effect of this will be to cause fluctuations in the frequency response of the system at kilohertz frequencies (for the sizes of typical recorders, the effect is much reduced at lower frequencies), and fluctuations in the directivity of the receiver. A full free-field calibration can be used to characterise the effects, but a better solution would be to deploy the hydrophone on a short cable so that it is not positioned adjacent to the recorder body. Some hydrophones are fitted with a protective guard in the form of a metal cage, which reduces the chances of damage to the hydrophone element. Although this protection is desirable, a poorly designed guard can influence the frequency response and directivity at kilohertz frequencies, and it is advisable to calibrate the hydrophone with the guard in place to determine the degree of influence.

Dynamic range: The dynamic range of the system is particularly important when measuring high amplitude sounds, and this information must be specified by the supplier so that the maximum undistorted signal level can be estimated, and any saturated signals eliminated during analysis of the data. With autonomous recorders, there is typically no opportunity to alter the systems settings (for example gain settings) *after* deployments, and therefore it is necessary to make an estimate of the maximum signal likely to be encountered during the deployment.

3.2 Calibration

3.2.1 System Calibration

For an absolute measurement, the sensitivity of the measuring system must be known. This requires that the system be calibrated. A laboratory calibration requires that the system undergo a series of measurements to determine the sensitivity. It is very risky to rely on indicative or nominal calibration values produced at the system design stage, and this is not recommended. The calibration should cover the full frequency range of interest for the specific application at hand. It is possible to calibrate a hydrophone and recording system with an overall uncertainty of better than 1 dB (expressed at a 95% confidence level). It is recommended that a full laboratory calibration is undertaken before and after every major deployment or sea-trial [IEC 60565 2006, ANSI S1.20 2012].

The system calibration can be undertaken either by full system calibration, or by calibration of individual components. For a full system calibration, the hydrophone is exposed to a known sound pressure field and recordings of hydrophone output are analysed. For calibration of individual components, the hydrophone is calibrated separately by an acoustic measurement, but the other components are calibrated using known electrical input signals. The components that require calibration are:

Hydrophone

There are national and international standards describing the calibration of hydrophones such as IEC 60565:2006 – *The calibration of hydrophones in the range 0.001 Hz to 1 MHz* (available in the UK as BS 60565:2007), or ANSI S1.20-2012 - *Procedures for calibration of underwater electro-acoustic transducers*. The calibration should conform to these procedures and be traceable to national or international standards maintained at a national metrology institute. Hydrophone calibration data are typically expressed in µV/Pa, or in decibels as dB re 1 V/µPa. Typically, it is expressed at a succession of discrete frequencies, or in the form of a calibration curve.

Note that at frequencies well below the resonance frequency, the hydrophone sensitivity should be invariant with frequency. However, as a hydrophone approaches its resonance frequency, the sensitivity cannot be considered to be "flat" and is likely to show variations in response. If the recorded data are already processed into third-octave bands before the correction for hydrophone sensitivity is applied, the required calibration values are the mean sensitivities for each of the frequency bands. Where the hydrophone sensitivity is not flat, a constant value across the band cannot be assumed. Note that if the hydrophone is placed close to a reflective boundary (such as a recorder case), interference from reflected signals will cause further fluctuations in the sensitivity with frequency. These effects are illustrated in Figure 3.2.

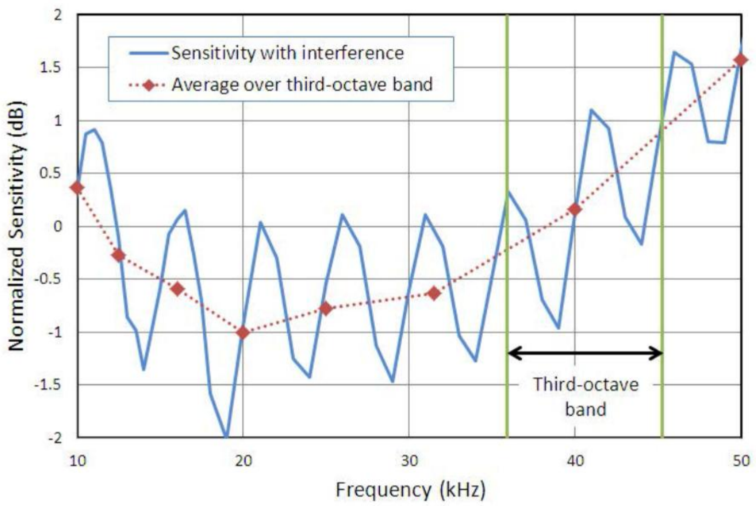

Fig 3.2: Examples of sensitivity fluctuations due to interference from reflected signals; the average sensitivity values for each third octave frequency band are also plotted.

Note that it is advisable to "wet" a hydrophone before deployment by cleaning the surface with a mild detergent. This will ensure that the surface is free of grease and dirt, and prevent air bubbles from adhering to the surface and causing distortion of the measured signal. Advice on wetting of hydrophones can be found at:
http://www.npl.co.uk/acoustics/underwater-acoustics/research/hydrophone-wetting

Note also that if extra cable is added to a hydrophone, this will *reduce* the overall sensitivity for hydrophones without an integral preamplifier. For hydrophones that have an integral preamplifier within the hydrophone body, adding extension cable will not affect the sensitivity. Information on how to correct for added extension cable may be found at:
http://resource.npl.co.uk/acoustics/techguides/loading/

Note that, for some hydrophones, the response may show a dependence on the type of mounting used. In this case, it is advisable to calibrate a hydrophone in the same mount as will be used in the field. Advice on the effect of mounting can be found at:
http://www.npl.co.uk/acoustics/underwater-acoustics/research/hydrophone-mounting

Note that, for some hydrophones, the response may show a dependence on the water temperature and depth of immersion. If the conditions for the calibration are significantly different from those during its use in the field, this may add uncertainty to the measurement. If there is evidence that the hydrophone performance varies significantly with temperature/depth, the calibration should be undertaken as close to the applicable conditions as possible, or corrections should be made using data for the variation in performance with temperature/depth. Alternatively, a hydrophone should be chosen which has a stable performance with temperature/depth (as far as possible). Advice on the effect of water temperature and depth of immersion for a range of common hydrophones be found at:
http://www.npl.co.uk/acoustics/underwater-acoustics/research/performance-of-commercially-available-hydrophones-with-temperature
and
http://www.npl.co.uk/acoustics/underwater-acoustics/research/performance-of-commercially-available-hydrophones-with-hydrostatic-pressure

Amplifiers

The performance is typically expressed as a gain factor, either in terms of a linear gain (eg x10) or in decibels (eg 20 dB). Note that the amplifier gain may not be invariant with frequency, particularly at the extremes of the operating frequency band.

Filters

The filter performance is typically expressed as an insertion loss factor, a positive number expressed either as a linear factor or in decibels. By definition, a filter response varies with frequency, and must be characterised over the full operating frequency range of the system. The use of filters may serve a number of purposes: (i) to provide an anti-aliasing function (a low pass filter designed to restrict the frequency content of the signal before digitisation to below the Nyquist frequency of the acquisition system); (ii) to reduce the influence of very low frequency parasitic signals (a high pass filter designed to cut out frequencies of less than 10 Hz which may be generated by non-acoustic mechanisms such as surface motion – such filters are commonly incorporated into commercial hydrophones which have integral preamplifiers); (iii) to provide some signal equalisation across the frequency range (usually, this involves a high pass filter with a modest slope which is designed to compensate for the frequency roll-off observed in typical ambient noise spectra, thus avoiding saturation of the ADC). If any of the above filters are used in the system, their performance may need to be known to correct the data before analysis.

Analogue to Digital Converter (ADC)
The range setting (full-scale) and the calibration factor of the ADC must be known. It is usually expressed as a scale factor. This scale factor will depend on the digital amplitude output values (counts) of the ADC for a stated input voltage, and is typically expressed as counts per volt. Note that this is not the same as the number of bits of the ADC. Typically, this calibration factor will be invariant with frequency, but could vary depending on the range setting of the ADC. Note that the scale factor used in generating the data files forms part of the ADC calibration factor. The scale factor should be supplied by manufacturer for commercially available digital recording systems, and may be checked by recording an electrical signal of known amplitude.

3.2.2 *In-situ* calibration checks

It is advisable to undertake *in-situ* checks on the system calibration just before and after deployment, and in between any repeated deployments [EU TSG 2014b]. To do this, it is advisable to make use of a commercially available hydrophone-calibrator, which provides the hydrophone with a signal of known amplitude at a single-frequency (commonly at 250 Hz). The calibrator typically consists of an air-pistonphone that generates a known sound pressure level inside a small coupler into which the hydrophone is inserted. The sound pressure depends on the free-volume inside the coupler when the hydrophone is inserted, and so the coupler must be calibrated for each type of hydrophone that is used with it.

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

3.2.3 *In-situ* QA checks

It is good practice to undertake Quality Assurance (QA) checks on the measured data before the end of the deployment or sea-trial [Harland 2008]. If a problem with corrupted data is discovered only after the return to shore base, it is usually too late to remedy the problem. However, early discovery of a problem may allow it to be solved during the deployment. Good quality assurance checks include:

- Visual display of measured data in real time during deployments provides confidence that data are present and are not exceeding the dynamic range of the system. This is possible for vessel-based deployments or shore-based cabled systems; this is only possible for autonomous recorders if they are fitted with some telemetry (for example, using RF transmissions or wi-fi);
- Audio playback of data through speakers during or after the data acquisition process also

provides a good check on data quality, and may indicate the presence of other vessels or noisy intruders (only useful for signals in the human audio band but for higher frequencies a circuit may be used to “down-shift” the frequency to the audible range);

- Read (and perhaps play back) recorded signals before the end of a trial as a check on quality of data – this includes data from autonomous recorders that have been recovered. If the equipment has failed or data are corrupted, there may be an opportunity to repeat the deployment (depending on circumstance);
- Check for unexpected transient signals, for example from biological noise and impacts on the hydrophone;
- Check that the signal level and frequency content is within expected range – for example, for ambient noise;
- Check that hydrophones deployed close together show similar signal levels – they should not be identical, but closely positioned hydrophones with signal levels differing by many decibels may be indicative of a possible error;
- It can sometimes be useful to deploy a local source (for example, a pinger) to provide a signal which all hydrophones receive – this cannot easily be used for calibration, but at least provides a check on system functionality.

3.3 Data storage

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

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

It is desirable that such calibration data information be included in a file header or log file so that the information is kept with the data. Without this information, the data file may essentially be “uncalibrated”. Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data [EU TSG 2014b].

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

Guidance on data storage is provided by the Marine Environmental Data and Information Network (MEDIN). The MEDIN guidance may be downloaded from:
www.oceannet.org/marine_data_standards/medin_data_guidelines.html

Summary: Measuring Instrumentation

Ensure measuring system performance is fit for purpose. Key performance parameters include:

- Sensitivity (3.1.1)
- frequency response (3.1.2)
- directivity (3.1.3)
- system self-noise (3.1.4)
- dynamic range(3.1.5).

The performance of any commercial off-the-shelf systems should be validated (3.1.6).

The measuring system should be calibrated over the full frequency range of interest (3.2.1). Ensure appropriate quality assurance procedures are applied to the measurement (3.2.2 & 3.2.3).

Data storage should ideally be lossless format and include all necessary metadata and calibration information (3.3).

4. Deployment for noise measurement

4.1 Measurement configurations

Approaches to measurement may vary depending upon the type of noise being measured, the environment, the deployment duration, the amplitude and frequency of the noise, the required accuracy of the noise measurement, the available resource to deploy the instrumentation, and the budget. The main aims of the measurement configuration chosen are to:

- sample the sound field at appropriate point(s) in the water column for the duration and range of conditions required for the application;
- minimise spurious sources of non-acoustic signals caused by the presence of the hydrophone and its platform, which contaminate the measurements and lead to spurious data.

There are a number of common approaches taken.

4.1.1 Vessel-based surveys

Vessel-based surveys have been widely used for a variety of acoustic monitoring operations. This involves deployment of hydrophones (either individually, or in arrays) from a vessel, with the analysis and recording equipment remaining on the vessel, which may be either anchored or drifting. In many respects, vessel-based surveys offer a good solution for the measurement configuration. The method has the advantage that deployments can be quick and mobile, and a relatively large area may be covered fairly cost-effectively. The risk of losing instrumentation is low, the data can be monitored as they are acquired (often in real time), and instrument settings may be adjusted in real time to provide the optimum settings to ensure high quality data.

However, there are some disadvantages, the most obvious being that it is usually not cost effective for the vessel (and the researchers) to undertake *long-term* deployments (for example, weeks, months or years), so the deployments tend to be relatively short. This may be acceptable where the noise source is present for a duration of a few hours; for example, measurement of a marine percussive piling sequence during offshore construction, or measurement of radiated noise from several transits of a ship under test. However, this is not suitable where longer-term deployments are required; for example where the intention is to sample the radiated noise under a wide variety of operational states, or sample the ambient noise under a wide variety of environmental conditions.

Vessel-based deployments may also suffer from types of platform-related noise not so frequently encountered with other types of deployment. These include noise from vessel engines and echosounders, wave "slap" on the vessel hull, and hydrostatically-induced signals due to surface wave motion (see Section 4.3). Noise measurements may be taken from a survey vessel or launch with its engine shut-down and the vessel drifting, minimising platform noise. In such cases the distance between the hydrophone and the source may be determined by use of the vessel GPS system and noted during each measurement.

4.1.2 Static systems (moored systems)

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

A bottom-mounted deployment is preferable to a surface deployment to minimise parasitic signals from the influence of surface wave action, to keep the hydrophone away from the pressure-release water-air surface, and to minimise disturbance by surface vessels. A number of typical deployment configurations are possible, many of which are presented in the scientific literature [e.g. Cato 2008, Dudzinski *et al*. 2011, Robinson *et al*. 2011, ANSI S12.64: 2009, ISO17028-1 2012].

An ideal deployment would allow data to be streamed directly to shore base, either by cable, or through satellite or modem link (though the latter is likely to limit the data bandwidth to be transmitted). Such a deployment has the advantage of near real-time data availability and enables checks of system functionality to be performed [André *et al*. 2011]. However, such configurations are expensive and not readily available commercially. Therefore, a more cost effective solution for most deployments are autonomous recorders with the data only available periodically after recovery [Wiggins 2003, Wiggins *et al*. 2007, Lammers *et al*. 2008]. Such devices are archival and store data on memory cards or local drives.

Recovery requires either an acoustic release system or a surface buoy deployed from a seabed anchor. Trawl protection may be required for some deployments, depending on the likelihood of disturbance by fishing vessels.

Static deployments have the disadvantage that they are by definition static, and so measure in only one location. They also have a higher risk of data loss (for example, by accidental damage or theft) and in tidal flow areas may suffer from parasitic noise effects such as cable strum or flow noise (see section 4.3).

In the case of mobile sources such as vessels, the most accurate measurements using static deployments are usually taken at a deep-water military noise range. The measurements are then taken in quiet sheltered waters, and background noise sources are minimised.

4.1.3 Drifting systems

Drifting systems may be vessel-based, but more recently drifting autonomous recorders are being used. These have the advantage that the effects of flow noise are minimised in high tidal flow areas [Wilson *et al* 2014]. Drifting autonomous recorders, or drifting recorders with radio transmitters such as sonobuoys, have been developed to move with the fluid flow, minimising the relative motion between hydrophone and the medium. These systems are highly suitable in high tidal flow areas (such as those encountered in the locations of tidal stream energy developments) for both baseline measurements of background noise, and assessment of radiated device noise. Typically, the system will consist of a hydrophone and recorder attached to a drogue or sea-anchor which causes the whole system to drift with the prevailing current. A GPS receiver is sometimes used to provide a log of positional data [Wilson *et al* 2014]. Note that a synchronised time stamp on the audio-track is needed to accurately link to the GPS time.

Such systems have the advantage of being less susceptible to flow noise, but may still suffer from parasitic noise from moorings and floats. Drifting systems are not suitable for long-term deployments (they require continual recovery and redeployment), and do not make a measurement in one location (this may or may not be desirable depending on the specific application). In the case of measuring radiated noise from a specific source, the range from the source is a crucial parameter and this will be constantly changing as the system drifts past the source. This problem can be mitigated if the drifting system has a GPS receiver to provide positional data from which the range may be calculated, but the azimuth angle from the recorder to the source will also tend to change as the system drifts past the source (leading to changes in sound pressure if the source has appreciable directionality). It is possible to use several drifting systems at once to partially get around the problem with directivity. Also, use of several systems at once allows the separation of time-dependence from special-dependence for time-varying sounds.

4.2 Hydrophone deployment

4.2.1 Hydrophone depth

The spatial distribution of underwater sound pressure is depth dependent. A stronger dependence on depth is present in the uppermost part of the water column, in particular within one quarter of an acoustic wavelength of the water surface (for sound at 100 Hz, one quarter of a wavelength is about 3.7 m; at 1 kHz, it is about 37 cm). This is mainly due to the pressure-release nature of the water-air surface, but also because of the constructive and destructive interference between the direct sound waves and the sound reflected from the surface. This latter effect is commonly known as the Lloyd's mirror effect [Urick 1983]. It is also possible for measurements made close to the bottom to be influenced by interference effects, especially if the bottom is reasonably reflective.

For measuring sound in the relatively shallow UK waters (for example, in the North Sea, Irish Sea, English Channel), it is recommended that (if possible) the measuring hydrophone be positioned in the lower half of the water column, ideally between ½ and ¾ of the total depth (measured from the sea surface) [TNO 2011b, Mueller and Zerbs 2011]. Note that in very shallow water, the tidal depth variation may have significant effect on the sound propagation and should be recorded accurately.

In some cases, there may be a need to select other hydrophone depths, for example in deeper water where positioning hydrophones at the depths stated above may be impractical. Also, there may be a specific interest in the impact of noise on species that reside certain depths (for example, closer to the sea bottom or near the sea surface). Also, some sources such as marine pile driving may generate surface waves on the seabed around the pile. The sound pressure and acoustic particle velocity associated with these ground waves decrease quickly when moving away from the seabed. Therefore, if investigating the impact on bottom-dwelling species, measurements would be required close to the seabed.

If hydrophones are deployed from the surface in the presence of strong currents, it should be remembered that the actual hydrophone position may be influenced by displacement of the cable under the influence of the current. Attaching the hydrophone to a supporting cable with a heavy weight at the end of the support cable will mitigate the effect, but some displacement may still occur (affecting the lateral position and the hydrophone depth). To be sure of the hydrophone depths, a depth sensor can be attached to the support cable adjacent to the hydrophone. Note that this may be less of a problem if the hydrophones are mounted near to the bottom rather than near the surface, but if bottom deployed hydrophones are on long riser cables they may also be subject to significant displacement and cable strum due to tidal flow.

4.2.2 Number of hydrophones

Generally, the use of multiple hydrophones and recorders increases cost and complexity. However, the use of more than one hydrophone per measurement location also has several advantages:

- Redundancy: if one hydrophone or measurement channel fails, there is a back-up;
- Dynamic range: two hydrophones may be chosen with different sensitivities, to mitigate the requirement for a larger dynamic range than can be covered by a single measurement hydrophone or channel;
- Spatial averaging: use of more than one hydrophone allows averaging of the measured data thereby minimising Lloyds Mirror effects which can be pronounced at specific frequencies and specific spatial locations.

If using two hydrophones in shallow coastal water, it is recommended that these be placed at two depths in the lower half of the water column, ideally between ½ and ¾ of the total depth (measured from the sea surface) with the separation between hydrophones maximised (as far as reasonably possible) [TNO 2011b]. Again, there may be practical limitations which militate against this choice, especially in deep water.

4.2.3 Examples of deployments

Figure 4.1 shows examples of deployment configurations that may be used. These are schematic representations, and are not necessarily to scale. Other examples of deployment configurations are available in the scientific literature [Cato 2008, Harland 2008, Dudzinski *et al* 2011, Robinson *et al* 2011, ANSI S12.64: 2009, ISO17028-1 2012].

The vessel-deployed system shows the use of a surface buoy to create a stand-off distance from the vessel (useful to minimise the effect of wave slap on the hull), and an elastic suspension to decouple the surface motion from the hydrophone and recorder.

A bottom-mounted configuration is shown with the hydrophones and recording pod deployed using a sub-surface buoy. The recorder could just as easily be placed on the seabed using a frame. An anchor and weight is used to prevent lateral motion in currents, and a surface buoy is shown to indicate the position for recovery. The recovery could also be expedited by use of an acoustic release (the surface buoy, or the whole system, is released from the weight on receipt of an acoustic signal).

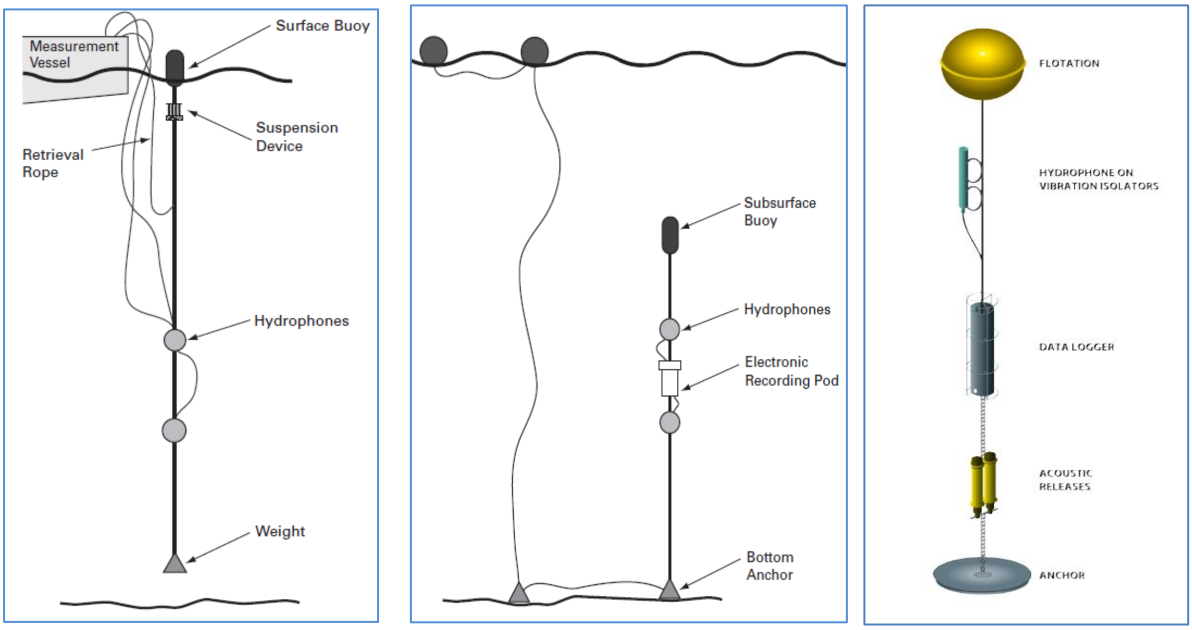

Figure 4.1: Examples of deployment configurations for systems, which are deployed from a surface vessel (left), bottom-mounted with surface float (centre), and bottom-mounted with acoustic release (right).

4.3 Deployment related noise sources

In addition to the self-noise of the measuring system itself (see Section 3.1.4), the measured data may also be contaminated by signals originating from the platform or method of deployment. This is often called “platform noise” or “deployment noise”. These parasitic signals are due to the deployment method for the hydrophone and recording system and its interaction with the surrounding environment (e.g. current, wave action, etc). Care needs to be taken in the design of the deployment systems to avoid contamination from these sources. Often, the presence of the contaminating signals is not easy to detect (even though it is present in the data). This makes it very difficult to remove the influence of these contaminating parasitic signals [Cato 2008, Harland 2008, ANSI S12.64: 2009, Robinson *et al*. 2011, Dudzinski *et al*. 2011].

The following illustrates some of the more common sources of unwanted parasitic signals that contribute to the platform self-noise of the deployed system, and provides advice with regard to mitigation.

4.3.1 Flow noise

Any flow of the medium relative to the hydrophone or cable can induce turbulent pressure fluctuations at low frequencies that will be sensed by a pressure sensitive hydrophone. This noise is produced in a turbulent layer around the hydrophone, and is analogous to wind noise on a microphone. It is not a true acoustic signal (it does not arise because of a propagating sound wave from a source remote from the sensor) and its existence depends upon the presence of the hydrophone (and its support structure) in the flowing water. It gives rise to low frequency signals (typically <100 Hz), with the frequency being dependent upon the hydrophone diameter and the speed of the current [Cato 2008, Ross 1987]. It can be the major source of deployment noise in high flow environments, for example in strong tidal currents. For autonomous recorders where the hydrophone is protruding from the recorder body, the problem can be exacerbated by turbulent flow around the end of the recorder casing or hydrophone guard. Strong fluid flow can also cause vibration of moorings and excite resonances in the recorder body.

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

Mitigation

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

The other main mitigation is to employ *drifting systems* where the system moves with the current and the relative motion of the hydrophone and medium is essentially zero [Wilson *et al* 2014]. These have some disadvantages as a deployment configuration, (see Section 4.1.3), but they are probably the preferred option for regions of very high current (for example, at the locations of tidal stream energy developments).

4.3.2 Cable strum

Cable strum occurs when cables are pulled taut by the action of currents, and the cable is then caused to vibrate by the action of the water flow around it, producing parasitic low frequency signals. The effect is similar to the "Aeolian harp" effect, or the singing of telephone wires in the wind. For typical cable diameters and currents, signal frequencies are of the order of 10 Hz (1 cm diameter cable in a current of 1 knot produces a signal of frequency 9 Hz) [EU TSG 2014b]. Even if the hydrophone is mounted on a rigid pole, severe current can induce the pole to "flap" and cause parasitic vibration.

Mitigation

The effect can be mitigated by use of bottom-mounted deployments, and by the use of mechanical fairings, often in spiral or helical form around cables and housings [Urick 1983, Ross 1987, Cato 2008]. However, bottom deployed hydrophones on long riser cables may be subject to significant displacement and strum due to tidal flow. If surface deployments are used, decoupling of the hydrophone from suspension cables using compliant couplings (for example, using elastic rope) will reduce the problem.

4.3.3 Surface "heave"

Any system deployed from the surface will have the potential to be affected by the action of waves or swell, which will cause changes in the hydrophone depth creating hydrostatic pressure fluctuations [Urick 1983, Cato 2008, Harland 2008]. These are sensed by the hydrophone and may saturate the ADC in the recorder because, although they are low frequency, they can be relatively high amplitude. Every 10 m of water depth is equivalent to approximately one atmosphere of static pressure. So, for the example of a 10 cm fluctuation in water depth at the hydrophone, there will be a 1 kPa pressure fluctuation (equivalent to 180 dB re 1 µPa).

<u>Mitigation</u>
The best solution to this problem is to mount the hydrophone from the seabed rather than the sea surface, using a bottom-mounted frame or sub-surface buoy arrangement. If surface deployments are used, decoupling of the hydrophone from the surface motion using compliant couplings (for example, using elastic rope and/or motion dampers) will reduce the problem (such a design is sometimes called an anti-heave suspension). Additionally, since the frequency of the signals is very low (<10 Hz), the use of a high pass electronic filter can eliminate the signals. However, this must be placed before the ADC to avoid saturation. A number of commercial hydrophones that have integral preamplifiers have built-in high pass filters with a cut-off of between 5 Hz and 10 Hz as mitigation for low frequency parasitic signals. However, such a system is not suitable if such low frequency signals are of interest.

4.3.4 Vessel noise

Where deployments are undertaken from a vessel, they should be made under quiet vessel conditions. Ideally, this means that the engines should be switched off, and as little noise as possible made on the vessel itself by machinery and crew. Preferably, the generator should also be switched off to avoid noise. This requires that the measurement instrumentation be powered from batteries. If the vessel is anchored, the anchor chain may be a source of noise. If the echosounder on the vessel produces frequencies within the frequency range of interest, this must also be switched off during the measurements. Another source of noise from vessel deployments is the noise of wave action on the vessel hull (sometimes called "wave slap"). This is worse for some types of hull, and may be reduced by orienting the vessel into the waves, and by deploying the hydrophones on long cables using floats or buoys to increase the distance from the vessel to the hydrophones; however, in practice this is difficult to eliminate completely. All of the above problems are reduced by avoiding vessel-deployment, and instead using a bottom-mounted deployment.

4.3.5 Mechanical noise

Mechanical noise includes (i) debris and/or sediment impacting the hydrophone; (ii) biological abrasion noise; (iii) hydrophone and cables rubbing against each other; (iv) mooring cables rubbing together. Any opportunity for parts of the mooring system to impact against each other will cause noise, which may be picked up by the hydrophone. This is especially true if the mooring involves metal parts which can come into contact (for example, chains) [Cato 2008, Harland 2008].

Mitigation

To minimise the problems: avoid using metal moorings if possible; avoid metal coming into contact with metal (such as with shackles); avoid the use of chains in the moorings and supports; avoid placing hydrophone so close to the seabed that sediment can impact on the hydrophone; avoid hydrophones touching the support cables by attaching them with vibration isolators (compliant couplings). It should also be noted that long-term deployments may need servicing at intervals to remove biological fouling.

4.3.6 Electrical noise

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

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

4.4 Auxiliary measurements

It is beneficial to record any auxiliary data that may be relevant, since these may be correlated with the measured noise levels during analysis. This is of general importance, but is particularly useful when measuring ambient noise data. This will enable an investigation of the dependencies of the measured data on other environmental factors such as weather. Some of the information may be obtained from other sources (for example, wind speed data), but if measured locally, this may require the deployment of auxiliary equipment. Depending on the availability this may or may not be possible, and any deployment of auxiliary equipment must not generate any additional noise.

Relevant auxiliary data to record may include:

- Sea-state
- Wind speed (and associated measurement height)
- Rate of rainfall and other precipitation, including snow
- Water depth and tidal variations in water depth (this can be measured using an echosounder)
- Water temperature and air temperature
- Hydrophone depth in the water column
- GPS locations of sources, hydrophones and recording systems
- Seabed type
- Profile of conductivity, temperature and hydrostatic pressure as a function of depth in the water column using a CTD probe - from this information the salinity, density and sound

speed profiles can be calculated from standard equations. Advice on the use of these equations is available at: http://resource.npl.co.uk/acoustics/techguides/soundseawater/

- Alternatively, the sound speed profile can be measured directly, using a velocimeter
- The pH of the seawater by use of a pH meter - an estimate of pH could be required for calculation of the absorption coefficient
- A monitor of the presence of vessels in the area where measurements are being made by keeping a log of the vessels visible; a receiver of ship traffic Automatic Identification System (AIS) is useful for larger vessels which have and AIS transponder
- The presence of any marine mammals in the area
- The presence of any distant noise generating activity such as geophysical surveying

Guidance on recording and storage of metadata is provided by the Marine Environmental Data and Information Network (MEDIN). Data guidelines are provided by MEDIN on the metadata requirements during collection of underwater noise. The guidance may be downloaded from: www.oceannet.org/marine_data_standards/medin_data_guidelines.html

4.5 Protection from damage/loss

Another factor when choosing final positions for deployment is the likely damage or loss of the equipment (and data) [EU TSG 2014b, 2014c]. This is a problem for long-term deployments using autonomous systems. The main dangers are from (i) extreme weather; and (ii) fishing activity.

Care should be taken to design the system to withstand severe weather. An appropriate weight and anchor should be used militate against movement under the action of tidal currents and storms. Any attempt to streamline the shape of the equipment should avoid creating an aerofoil effect under high flow conditions, which will tend to lift the item off the seabed.

Special concern should be given to avoiding damage from fishing. Some bottom-mounted designs have used an enclosed, cage-like form to protect against the system being caught and retrieved by fishing nets. However, in such cases, there may still be damage to hydrophones and cables, even though trawling is normally done at low speeds (less than 5 knots). It is better to avoid fishing areas altogether if possible. If there is information on fishing activities in the local area, for example by using VMS (Vessel Monitoring System) data, the areas to be avoided can be identified. Ideally, the location can be adjusted to an area with lower fishing frequency, thereby minimizing the probability of loss due to trawling. Furthermore, information on shipwrecks can be used to avoid fishing activities as well. Areas containing shipwrecks are often avoided by fishermen, and so choosing a location in the vicinity of a wreck can help to minimize the risk.

Before deployment, all relevant local authorities should be informed. This includes all necessary consenting authorities and any relevant stakeholders (such as fishing industry, shipping and navigation). It could be advantageous to increase awareness by publicising the deployment in the local community via notices to mariners and the Kingfisher bulletin. All equipment should be labeled so that if accidentally retrieved or found, it may be returned (the use of GPS trackers may help retrieval). Radar reflectors fitted to buoys will help avoid damage by collision (and reduce any hazard to shipping).

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

Summary: Deployments

Ensure deployment configuration is appropriate for measurement requirements with hydrophones deployed at appropriate depths (4.1 & 4.2).

Ensure deployment related parasitic signals are minimised, including those originating from:

- Flow noise (4.3.1)
- Cable strum (4.3.2)
- Surface heave (4.3.3)
- Vessel/platform noise (4.3.4)
- Mechanical noise (4.3.5)
- Electrical noise (4.3.6)

Record all auxiliary data and metadata (4.4).

Ensure steps are taken to protect recorders and data from loss (4.5).

5. Ambient noise

5.1 Definition

Perhaps surprisingly, there is no universally applied definition of ambient noise in the ocean. In common usage, the exact meaning depends on the context, with the differences in meaning depending on whether local sources of anthropogenic sound are excluded. However, ambient noise (sometimes simply referred to as "background noise") may be clearly distinguished from *radiated noise* (sound radiated by a specific source under study), and *self-noise* (the noise generated by the recording equipment and its deployment/platform).

Many of the subtle differences in the definition of ambient noise often relate to the motivations for measurement, which generally fall into two categories:

- Measurement to determine the background noise during the study of a specific source of radiated noise – in essence, this is required to assess the "signal-to-noise ratio";
- Measurement to characterise the ambient sound in specific locations, sometimes termed the "soundscape".

In the first of these, the definition of ambient noise would exclude the radiated noise from the specific source under study (sometimes termed the "signal" as in "signal-noise ratio"), and the ambient noise would be measured when the source was silent (or absent).

In the second case, it is not clear that any sources of sound should be excluded *a priori*. However, the most common "classic" definition of ambient noise is [Knudsen 1948, Wenz 1962, Urick 1983, Cato 2008, Carey and Evans 2011]:

Background acoustic noise without distinguishable sources.

This definition has the problem of how to identify "distinguishable sources", and how to eliminate them from the measurements. The motivation behind a definition such as this is an attempt to determine a "typical" value for background noise that is unaffected by infrequent "loud" events, such as the occasional passage of a ship very close to the measuring hydrophone.

Because it is difficult to eliminate the influence of individual sources within measured data, and because all sound has the potential to contribute to stress of marine species (through masking effects, etc), recent attempts to define ambient noise have tended to encompass all sound reaching the measurement hydrophone from all sources. Measurements to characterise the ambient sound in a specific location are becoming more common as interest grows in the trends in anthropogenic sound in the ocean, for example in response to the EU Marine Strategy Framework Directive [EC 2010, EU TSG 2010]. In the 2014 report of the EU Technical Sub-Group on Noise [EU TSG 2014b], *in the absence of a specific signal* the ambient noise is defined as:

> *All sound <u>except</u> that resulting from the deployment, operation or recovery of the recording equipment and its associated platform, where 'all sound' includes both natural and anthropogenic sounds.*

Here, no attempt is made to exclude any sources of sound. However, in this definition, explicit mention *is* made of the contaminating signals to be excluded from the ambient noise analysis: all signals produced because of the perturbing effect of the recording system itself and which would not be present in the absence of the system and its platform.

In summary, the ambient noise ***<u>never includes</u>***:

- Self-noise of the recording system (see Section 3.1.4);
- Platform noise from the deployment, operation and recovery of the instrumentation (see Section 4.3).

5.2 Sources of ambient noise

Ambient noise is the combination of contributions from many different sound sources, each differing in behaviour, and in temporal and spatial dependence [Urick 1983, Hildebrand 2009, Ainslie *et al* 2009] and there has been some concern with regard to potential increases in anthropogenic noise [Andrew *et al* 2011, MacDonald *et al* 2006]. Although there are many sources, much of the ambient noise can be expressed in terms of a relatively small number of generic components, each produced by the contributions of a particular type of source.

The most effective way of characterising, predicting or forecasting the noise is to characterise the behaviour of the individual components, each showing temporal and spatial variation related to behaviour of the sources. Early studies of ambient noise established the main components of ambient noise as [Urick 1983, Carey and Evans 2011]:

- *sea surface noise*: the noise of wind and wave action at the surface, usually referred to as *wind-dependent noise*, and rain noise;
- *biological noise*, the noise of fish, mammals and invertebrates;
- *natural seismic/geoacoustic noise;*
- *traffic noise*, the noise of distant shipping.

Figure 5.1 shows the typical levels of ambient noise in the *deep* ocean.

An important fact to appreciate is that ambient noise levels can show significant variation over time. The observed temporal and spatial variation in ambient noise level can be tens of decibels (in other words, the amplitude can vary by orders of magnitude). This fact should be evident from the fact that some sources are weather dependent. This variation can be in the short-term of minutes and hours, or a medium-term such as a diurnal variation (day to night), variation with tidal flows, or a longer-term seasonal variation. Biological noise can depend on time of day and season. The noise level can also depend on location, an example of one cause of this being proximity to a shipping lane, another being proximity to a biological source such as snapping shrimp.

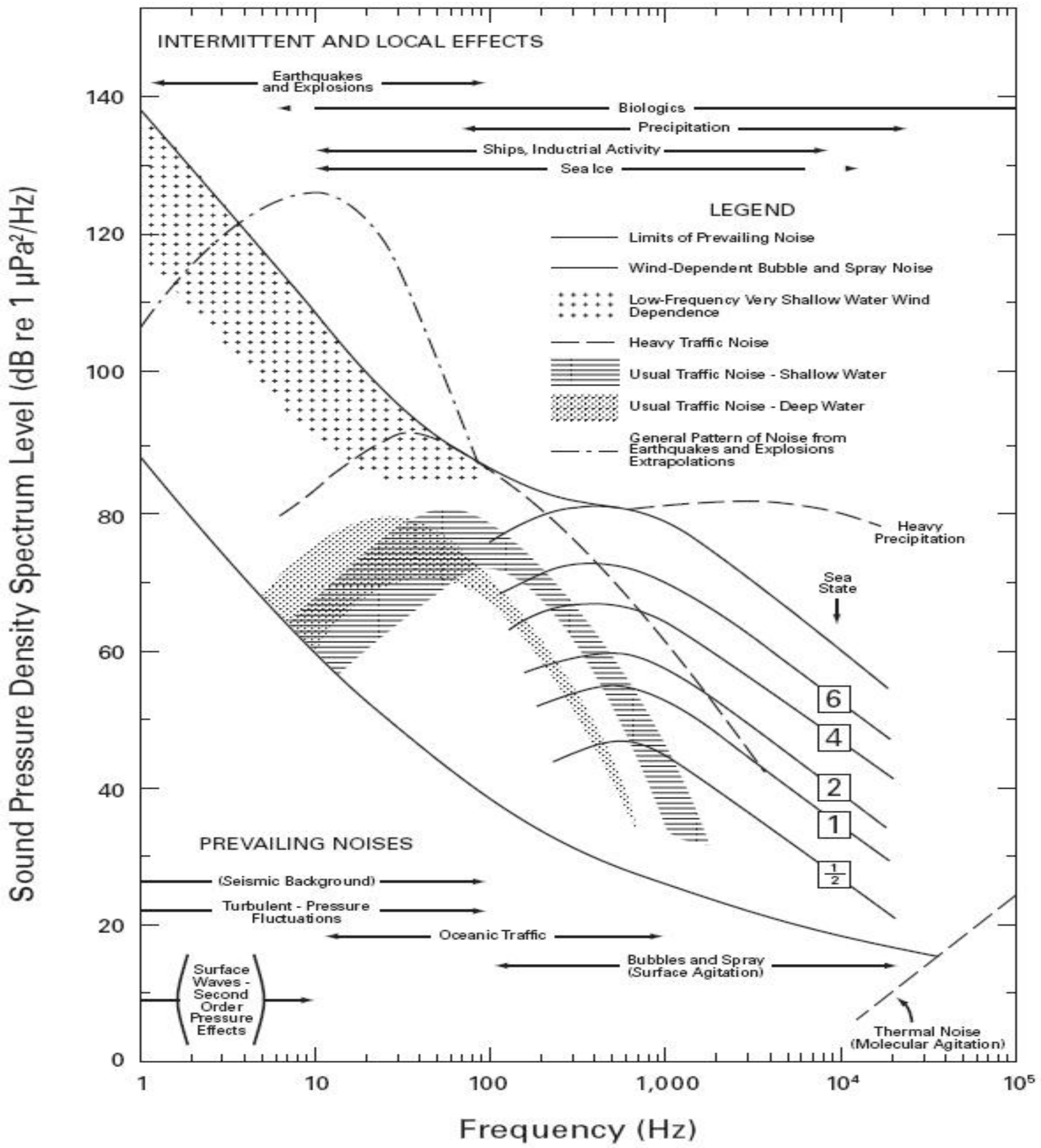

Fig 5.1 Typical spectral density levels for common sources of ambient noise in the ocean. The plot has been redrawn, but is based on a plot in Richardson *et al*, 1995.

5.3 Measurement

5.3.1 Sampling

Since ocean ambient noise can show significant variation, both spatially and temporally, any attempt to measure the noise inevitably involves sampling due to the choice of where to measure, and when to measure in time (and for how long).

Temporal sampling

The sampling methodology adopted may be influenced by the purpose of the measurements. If the objective is merely to determine the background noise levels that influence a measurement of radiated noise from a specific source, it is acceptable to take a *snapshot* of the noise from a short-term deployment over a relatively short time period (perhaps a few hours), before and/or after the measurement of radiated noise from the source under test. Here the purpose is really to ensure that sufficient signal-to-noise ratio is available during the characterisation of the specific source under test, and the measurement of ambient noise is not the main objective of the exercise.

Where the objective is to determine the change to the overall background noise caused by the presence of a specific activity (for example, the installation of a marine renewable energy development or oil and gas platform), a medium-term deployment of perhaps a few weeks is more appropriate. The benefits of very long-term deployments may not be worth the costs in such cases. An example of such an activity might be the construction phase of a renewable energy development, or the installation and operation of an offshore oil and gas platform. Here, it is important to sample the range of conditions that give rise to the statistical variation in noise levels. As a minimum, the diurnal and local tidal variations should be encompassed by the measurements, and there should ideally be enough time to cover variation in local shipping traffic. Depending on the season, it may not be possible to sample all weather conditions in a medium-term deployment, and this can bias the measurement data. In the case of medium-term deployments, the weather conditions should be recorded and stated with the results, and the results may only be used as representative of the actual conditions pertaining during the measurements.

Where the objective of the measurements is to comprehensively characterise the ambient noise in specific locations or in specific regions, long-term measurements are required. These should be designed to sample the noise on a time-scale appropriate to meet the objectives of the work. A full characterisation may require that the measurement system be deployed on a semi-permanent basis.

Note that short and medium term deployments do not generally sample the whole range of values of the ambient noise. The time duration and environmental conditions must be stated along with the results. In summary:

> *a relatively short-term measure of the ambient noise should not be used as representative of the ambient noise at that location for any time other than the period of time during which the measurements were undertaken.*

Duty cycle

Short-term snapshots and medium-term deployments may be made using continuous recordings. However, for long-term deployments there will be a trade off between overall length of recording, storage capacity, sampling rate, resolution and power consumption (battery duration).

To enable longer-term deployments, a duty cycle may need to be adopted where the recorder is on for only part of the time. In such cases, the appropriate duty cycle will depend on the objective of the measurements and the limitations of the equipment, but a duty cycle that has a periodically spaced “on time” is a reasonable choice unless there is a desire to sample the noise at specific times to capture specific events. One common strategy when continuous recording is not feasible is either to “decimate” down the duty cycle, or to reduce it by a power of two (for example, five minutes on, five minutes off).

Spatial sampling

Consideration should also be given to the spatial sampling required. It may be necessary to make measurements at one or more sites to get a good understanding of the ambient noise field. If an estimate is required of the overall ambient noise in an area, it is preferable that the hydrophone is not positioned close to a loud local source of noise that will dominate the noise field.

In deciding the location for long-term noise monitoring, considerations should be given to the water depth at the measurement location. For sound propagation in shallow water, there is a lower cut-off frequency below which sound will not propagate (see Section 7 for details). If low frequency sound is of interest, then the location should not be chosen to be so shallow that low frequency sound from distant sources (such as shipping) will not reach the hydrophone. It is preferable that the location has a relatively smoothly varying bottom bathymetry (locations adjacent to sand banks or trenches are undesirable), and the seabed or sediment should preferably be typical of the area being monitored.

With the adoption of the EU Marine Strategy Framework Directive (MSFD), monitoring at frequencies relevant to shipping noise has become of increasing interest. Here, the desire is to use a monitoring hydrophone to integrate the noise radiated by all shipping traffic in a specific region, examining the overall levels and trends. In general, it is preferable to choose locations that are:

- away from loud local sources of noise which may dominate the soundscape;
- adjacent to and with clear visibility of busy shipping lanes without significant bathymetry features in between (sand banks or trenches);
- not directly under a specific traffic route (such as a ferry route);
- away from fishing areas where disturbance/damage from trawling is likely.

The 2014 reports by the EU TSG Noise have made a number of recommendations to member states with regard to choice of positions for monitoring stations for large-scale long-term monitoring in response to the MSFD, and some of these are more generally relevant [EU TSG Noise, 2014b]. The recommendations are summarised below:

- Where there are few measuring stations per basin, priority should be given to monitoring in order to ground truth predictions (category A), since this monitoring is less sensitive to the influence of individual ships that might bias the averaged sound pressure levels. Monitoring may be more cost effective if existing stations are used for monitoring other oceanographic features;
- Member States should make sure that they have access to data on the noise characteristics of individual ships
- In deep water, monitoring devices to ground truth predictions (category A) should be placed in areas of low shipping density. The range at which elevated noise levels may occur is greater in deep water as low frequency sound can propagate long distances;
- Consider local topography and bathymetry effects e.g. where there are pronounced coastal landscapes or islands/archipelagos it may be appropriate to place hydrophones on both sides of the feature;

- In waters subject to trawling, use locations that are protected from fishing activities or locations where trawling is avoided due to bottom features (e.g. underwater structures/wrecks) and/or to use trawl safe protection;
- As far as possible avoid locations close to other sound producing sources that might interfere with measurements e.g. oil and gas exploration or offshore construction activities. Areas of particularly high tidal currents may also affect the quality of the measurement;
- In all underwater noise monitoring, the location should be chosen taking into account site-specific properties such as tide, sediment and currents; it is important that the rig is silent and rig design should take account site-specific considerations.
- Calibrate sensors before deployment, if possible at the same pressure/temperature as encountered at the planned deployment depths.

5.3.2 Frequency range

The frequency range over which measurements are made will depend on the objective of the measurements. For example, if the purpose is related to the potential for impact on marine species, the frequency range of hearing of the marine receptors may govern the frequency range of the measurements.

Note that criteria stated in Section 3.1.2 apply, for example with regard to sampling frequency for ADCs.

Making accurate measurements of ambient noise at the extremes of the frequency range is difficult. At frequencies less than 20 Hz, it is difficult to isolate the measuring system from the low frequency parasitic signals described in the previous sections. At frequencies greater than a few tens of kilohertz, measurements are often limited by self-noise of the measuring system (see Section 3.1.4). Although theoretically the ambient noise is dominated by thermal noise at such high frequencies, it is difficult to measure such low noise levels, and in areas of shipping traffic recorded levels may be dominated by high frequency echosounders from nearby vessels.

5.3.3 Equipment and deployment requirements

The key performance criteria for equipment, instrumentation and deployment are listed in detail in Section 3 and Section 4. For measurements of ambient noise, the following are of particular importance:

- **Self-noise**: a low self-noise system should be used for measuring ambient noise (Section 3.1.4);
- **Platform noise**: steps should be taken to minimise noise from deployment platforms (Section 4.3)
- **Sensitivity**: in general, the sensitivity of the system should be high (Section 3.1.1), and for coverage of high dynamic range across the frequency spectrum, consideration should be given to using multiple channels with different sensitivities (Section 3.1.5)
- **Calibration:** the recording system must be calibrated before deployment (Section 3.2);

- **Data storage**: see Section 3.3;
- **Auxiliary data**: it is important to record metadata so that noise levels may be correlated with environmental data (eg weather) or ship traffic data (see Section 4.4);
- **Protection from loss/damage**: an important topic to safeguard data in long-term deployments (Section 4.5).

5.4 Data analysis

5.4.1 Objectives

When undertaking data analysis of ambient noise, the motivation for the measurement can be a determining factor in the analysis method chosen. The analysis may have a number of aims:

- To provide a descriptor of the overall noise level due to all noise sources in the location, perhaps to evaluate the effect on marine species (eg from masking);
- To characterise the nature of the noise and the soundscape;
- To provide a descriptor of the typical background noise in the location in the absence of temporary or transient events;
- To determine the performance of a system in the presence of known background noise;
- To compare the noise levels with those in other locations;
- To determine trends in noise levels;
- To provide a measure of background noise to estimate the spatial range of audibility of a specific sound source.

The analysis methods used and the metrics and estimators chosen will depend on which of the aims listed above are of interest.

5.4.2 Frequency representation

Noise data are usually represented in the frequency domain, although occasionally a time-domain waveform of a transient event will be displayed.

It is recommended that ambient noise data be displayed at minimum in third-octave bands. This simplifies the data, and is appropriate for most considerations of environmental impact. However, where narrow-band features exist in the data (such as tonal components from specific sources), narrow-band analysis may be required to illustrate these features (tonal components will not be apparent in third-octave band analysis).

To illustrate the temporal variation in frequency content for a time-varying signal, a time-frequency representation is recommended such as a spectrogram or waterfall plot. In a spectrogram, the spectral levels are represented using a colour mapping, with time and frequency on the horizontal and vertical axes and a clearly defined colour scale. It should be noted that care must be taken when interpreting spectrograms. A choice must be made on the filter bandwidth (or FFT settings) to be used: wide-band spectrograms provide high time resolution and narrow-band spectrograms give high frequency resolution. There is a time-bandwidth trade-off which means that emphasising one loses definition of the other. The optimum choice depends on the type of sound and the information that is required from the spectrogram. For example, a narrow filter bandwidth used with repeated pulses can smear them and give a series of frequency striations so that the repetitive nature of the sounds is lost. When referring to the primary frequency of harmonic sounds, it is important to state whether frequency is that of the lowest harmonic (the fundamental), or the strongest harmonic (the highest amplitude), or the repetition frequency.

It is most common for noise signals to be represented in the frequency domain as noise spectral levels plotted as a function of frequency. The data for ambient noise is usually expressed as spectral density levels, where the data in each frequency band had been normalised by dividing by the bandwidth of the frequency band. The units of the levels in each band are then dB re 1 μPa^2/Hz. (Note that these units are sometimes expressed as dB re 1 μPa/√Hz).

5.4.3 Metrics

The most appropriate metric for expressing ambient noise is Sound Pressure Level (SPL).

When analysing noise, it is necessary to average the measured data. This is because the instantaneous values of the sound pressure are fluctuating continually, and any snapshot at a specific instant in time cannot represent the statistical variation in the values. When averaging noise, it is necessary first to square the data (since sound pressure has both positive and negative excursions, the unsquared data will tend to average to zero). Therefore, the noise values are most often stated as mean square values, or in terms of root mean square (RMS) values.

Note that in the definition of SPL in Section 2, the quantity is already defined as an average quantity. This may be calculated from either a mean square sound pressure or an RMS sound pressure (see Section 2).

To undertake data averaging, the measured data are divided into analysis time windows, or "snapshots". For each snapshot time sequence, the SPL is then calculated at each frequency of analysis (typically, for each third-octave band). This will result in a sequence of SPL data for each frequency band, and these data are then processed in the manner described in Sections 5.4.4 and 5.4.5 to provide averaged levels and the statistical variation of the data.

The choice of snapshot time will depend on the nature of the data available (there may be some data sampling restrictions imposed by the measuring instrumentation). For example, if the duty cycle involves recordings of 5 minute sequences, then the snapshot time cannot be longer than 5 minutes (though it could be shorter).

The processing into third-octave bands is often accomplished with digital filters or with Fast Fourier Transform processing, and for accurate representation of third-octave band levels at low frequencies, a long snapshot time is required (sufficient accuracy at 10 Hz requires a snapshot time of at least 30 seconds).

5.4.4 Averaging methods

There are a number of averaging techniques that have been used for ocean noise data, and several papers in the scientific literature that compare the utility of the different methods [Merchant *et al* 2012, Van Der Schaar *et al* 2014]. In addition, the 2014 reports by the EU TSG Noise have made a number of recommendations with regard to averaging of noise data in response to the MSFD [EU TSG Noise, 2014a, 2014b, 2014c].

When considering different methods, depending on the aim of the analysis, the methods may be judged against a number of criteria. Ideally, the metric produced by the method would be:

- Robust to minor changes or differences in implementation (for example, choice of different snapshot times);
- Produce values that are physically meaningful;
- Simple to implement;
- Compatible with comparable regulations or procedures (for example, those used in airborne acoustics for environmental noise assessment);
- Insensitive to occasional very loud transient events that might bias the data.

There are number of common averaging metrics that have been used:

<u>Arithmetic mean</u>
This is the average of the snapshot values expressed as mean square sound pressures (or RMS values). This has the advantage that it is robust – it is invariant with choice of snapshot time. This means that comparisons may be made with other researchers who have used different snapshot time windows (perhaps because of restrictions posed by different instrumentation or sampling regimes). It has a physical meaning in terms of the average sound pressure in pascals, and is compatible with the averaging metrics used in standards for airborne sound. However, it is sensitive to being influenced by very high amplitude sounds that may occasionally be received – for example if a ship comes very close to the monitoring station. On such occasions, the sound pressures can be orders of magnitude higher than the minimum values experienced, and if there are a sufficient number of such occasions, the arithmetic mean can be biased to a high value than the median.

<u>Median</u>
This is the median of the snapshot values, which is equivalent to the 50th percentile. This value *does* depend on the chosen snapshot time, but is much less influenced by the high amplitude transient events [Merchant *et al* 2012, Van Der Schaar *et al* 2014]. The median value can be thought of as more representative of the background noise level in the absence of the high amplitude events.

<u>Geometric mean</u>
The geometric mean of the snapshot values is equivalent to calculating the arithmetic mean on the values of the levels in decibels. It is easy to calculate if the data are already available in decibel form, but the value calculated depends on the snapshot time chosen and its physical meaning is uncertain.

<u>Mode</u>

The mode of snapshots values is equivalent to the maximum of the probability distribution. Although of some statistical relevance, its physical meaning is uncertain. This metric is not recommended.

It is recommended that for the expression of ambient noise values, the following metrics be used:

- **arithmetic mean**
- **median**

Note that these quantities may still be expressed in decibels, even though the averaging does not take place using the decibel values.

When an average value for ambient noise is established using the arithmetic mean, the value found for the average will be dominated by the noisiest contribution. Therefore, when monitoring in the vicinity of established high shipping density areas (such as commercial traffic lanes), the arithmetic mean is likely to be dominated by this contribution. The difference between the arithmetic mean and median is one indicator of the skewness of the distribution of sound pressure levels.

Figure 5.2 shows the two metrics calculated for SPL data averaged over a snapshot time of 1 minute in the 125 Hz third octave band, the measurements being made off east coast of the UK over a few days. Occasional transients in the data may be observed due to the close proximity of vessels in the area. The median value (81 dB re 1 µPa) is insensitive to these high level transients, but the arithmetic mean (84 dB re 1 µPa) shows a higher level due to their effect. The maximum and minimum values are also shown.

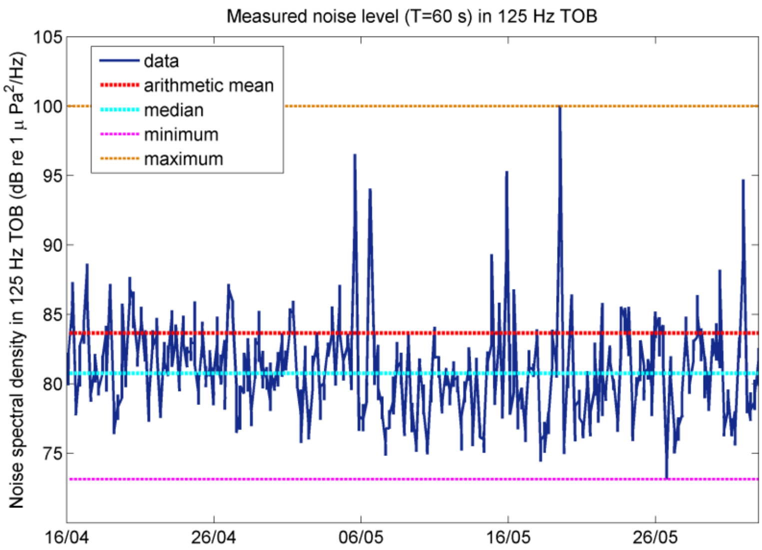

Figure 5.2: Example of ambient noise measurement in the 125 Hz third octave band made off east coast of the UK. The data shown are for the SPL averaged over 1 minute and plotted over a duration of several days. Two types of metric are displayed: the arithmetic mean, which is affected by the presence of high amplitude transients, and the median. The maximum and minimum values are also shown.

5.4.5 Statistical representation of noise

The metrics described above are not sufficient to describe the ambient noise because they contain no information about the dispersion of values – the range of values obtained from the averaging procedure described in Section 5.4.4. The 2014 report by the EU TSG Noise [EU TSG Noise 2014c] and other studies [Merchant *et al* 2013, Van der Schaar *et al* 2014] recognised that additional statistical information about the noise distribution is necessary, and recommended that the complete distribution be retained for this purpose in suggested bins of 1 dB.

The distribution of values for each frequency band may be displayed in a number of ways. One classic way is in the form of a "box plot" – a common way of expressing statistical information showing the median or mean and selected percentiles (many software packages are able to display data in this form). Figure 5.3 shows some data displayed in this format. There is usually some flexibility with regard to which percentiles are shown, and whether the absolute maximum and minimum values are also plotted.

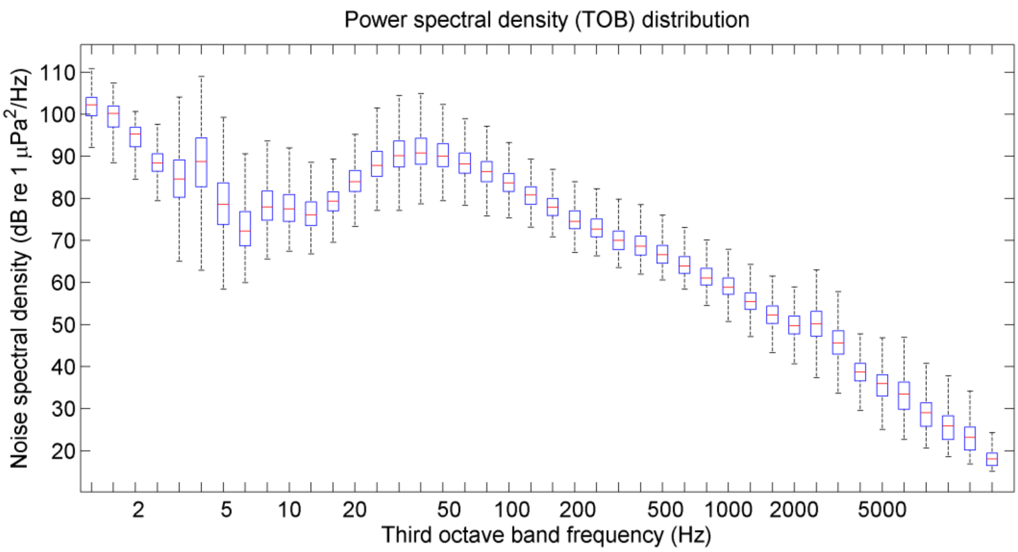

Figure 5.3: Statistical representation of the measured sound pressure level third octave bands in a box plot form showing the median (red line), and percentiles at 5, 25, 75, and 95%.

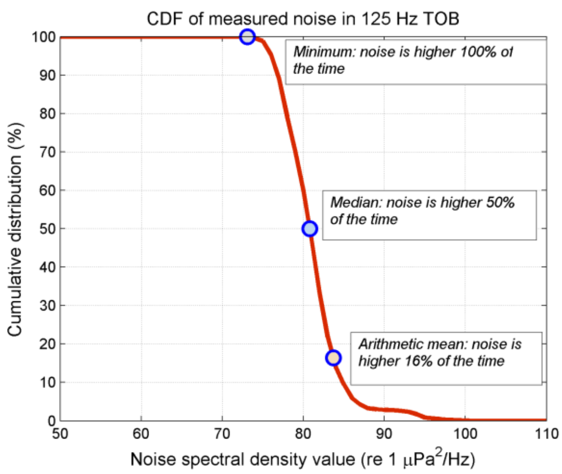

Figure 5.4: Statistical representation of the measured sound pressure level in the 125 Hz third octave band as a cumulative distribution function, showing the percentiles or the exceedance levels. The curve shows the proportion of time where a given minimum level is reached. For example, it shows that 50% of the time, the measured level exceeds the median level of 81 dB re 1 μPa, and that for only 16% of the time does the level exceed the arithmetic mean.

In addition, in order to establish the statistical significance of any change in the noise level, the distribution in the form of percentiles of the cumulative probability density function is also useful. An example is shown in Figure 5.4. The plot shows the corresponding percentage exceedance levels. The 50 % exceedance level is also the median. The term ‘exceedance level’ is preferred to ‘percentile’ because ‘10th percentile’ can mean either the value exceeded 10% of the time (10% exceedance level) or the value not exceeded 10% of the time (90% exceedance level). For further guidance, see ISO 1996-1:2003, [ISO 2003].

Summary: Ambient noise measurement

Ensure that the objectives of the measurements are clear and that the monitoring and deployment configuration is appropriate for those objectives (5.1 & 5.3).

Ensure that the temporal sampling regime is appropriate for the objectives, and that the duration and duty cycle are appropriately chosen (5.3).

Ensure that the spatial sampling regime is appropriate for the objectives, and that the locations of monitoring stations are appropriately chosen (5.3).

Ensure that the instrumentation is correctly specified for the application (for example, in terms of frequency range, dynamic range and self-noise) (5.3.2).

Ensure the deployment minimises measurement artefacts and parasitic signals (5.3.3).

Document and justify choice of data analysis methodology in terms of:

- Metrics – arithmetic mean and median are recommended (5.4.3);
- Averaging procedure – choice of snapshot time (5.4.4);
- Statistical representation of data – representing dispersion of data by use of analysis such as box-plots, and cumulative distributions (5.4.5).

Record all relevant auxiliary data and metadata including data which may correlate with acoustic data (ship traffic data, weather data, etc) (5.3.3).

6. Radiated noise

6.1 Characterisation of sound sources

Radiated noise is the sound radiated by a specific source. This is distinct from ambient noise, which is the noise received from many indistinguishable sources.

The noise source in question could be a source such as a ship, a marine renewable energy development, or an oil and gas platform. The noise of interest could be construction noise (for example, marine pile driving or drilling), or it could be noise radiated during operation. To characterise the noise radiated by the source, it is necessary to consider a number of factors.

6.1.1 Frequency content

The frequency content of the source must be described in order to fully characterise the source. This means that the radiated noise must be measured using a hydrophone and system that is capable of faithfully recording all the major frequency components within the radiated noise spectrum. When characterising a source for the purposes of environmental impact assessment, the frequency range required may also be governed by the hearing range of relevant marine receptors.

It is common to express the radiated noise as a spectrum in third-octave frequency bands. Although this simplifies the data, it is usually sufficient for the purposes of environmental impact assessment.

However, narrowband frequency analysis may be desirable, especially if the motivation is to diagnose specific noise generation mechanisms within the source (perhaps with the ultimate aim of noise quietening). In this case, narrow-band analysis is a valuable analysis tool. A classic example of the usefulness is in ship noise measurement where it may be necessary to determine the cause of specific components within the radiated noise spectrum [ANSI 2009, ISO17028-1 2011, Arveson and Vendittis 2000, Wales and Heitmeyer 2002, Bahtiarian and Fischer 2006].

6.1.2 Temporal variation

If the acoustic output varies with time, then the measurements must sample the range of variations. This may require the measurements to be undertaken for an extended period rather than a short snapshot. An example of a time varying acoustic output is the soft start period during marine pile driving [Robinson *et al* 2007], or the operational noise of an offshore windfarm or a wave energy device where the noise output depends on the operational conditions [Lepper *et al* 2012, Robinson and Lepper 2013].

6.1.3 Source directivity

Many sources of anthropogenic noise may radiate noise asymmetrically both in horizontal and vertical planes. Examples include ship noise where the beam aspect radiation may be higher than the bow or stern aspect (where there is some shielding by either the body of the ship or the wake).

Another example is a tidal stream device, which may have different source directivity properties in different directions (for example perpendicular to and in the plane of the blades).

The source directivity patterns may also vary with acoustic frequency. Detailed assessment of complex directivity patterns may not be cost-effective, or may be impractical. An assessment must be made of the relative importance for specific requirements. For example, audibility in the assessment of collision risk to tidal turbines may be most appropriate for an animal moving with the tidal flow - typically perpendicular to the plane of the blade movement or within a confined channel depending on perceived most likely behaviour.

6.1.4 Near-field and far field

If measurements are required close to the source, this may be in the acoustic ***near-field*** of the source. The acoustic near-field is the region close to the source where the field exhibits considerable interference between sound waves emanating from different parts of the source structure [Kinsler *et al* 2000, Urick 1983]. In this region, the spatial-distribution of field amplitude is quite complex with maxima and minima evident, and with the sound pressure and particle velocity generally out of phase. Without a physical model of the source vibration, it is difficult to draw significant conclusions about source acoustic output from individual measurements made in the near-field. To fully characterise the acoustic field requires a measurement scan to be undertaken using a hydrophone over a surface enclosing the source (an impractical requirement for measurements in the ocean, but feasible for sonar sources using sophisticated facilities) [Williams 1999].

The majority of measurements made of radiated noise are undertaken in the acoustic ***far-field***. The far-field is the region far enough away from the source that the sound pressure and particle velocity are substantially in phase, and all sound waves appear to be emerging from a point (usually termed the acoustic centre of the source). In the acoustic far-field, if there are no boundaries to reflect the sound (and ignoring sound absorption in the water), the sound pressure should fall off inversely with distance from the source (a 6 dB reduction in SPL per doubling of distance).

Making good quality far-field measurements may be difficult for large distributed sources that are relatively quiet. This is because at sufficient range to achieve far field conditions, the noise radiated by the source may no longer be measurable above ambient noise, or may be masked by other nearby sources.

6.2 Source output metrics

To quantify the acoustic output of a source, it is necessary to define an appropriate acoustic metric. There are several methods to do this. The most desirable is to derive a source output metric for the source that is independent of the environment and which may be used with some predictive utility for modelling the sound field produced by the source when placed in another location. However, this is not always straightforward, and other metrics are sometimes used.

6.2.1 Received level at a fixed location

For this metric, a measurement is made of the sound field at a specific location, and this is taken as indicative of the source output. This has the advantage that the measurement is simple and requires little post processing, and does not require that measurements be undertaken as a function of range [Hazelwood and Connelly 2005].

The results are usually stated for a reference distance, for example 750 m from the source (a reference distance commonly used for windfarm construction noise in Germany). If the measured data are not acquired at exactly this distance, they may be "corrected" to the standard reference distance by means of a simple propagation law without significant error [Mueller and Zerbs 2011].

This output metric has the disadvantage that it has little predictive utility and cannot be used to predict the sound field produced by the source when placed in another location with different conditions (water depth, etc). As a comparative method, The method works best when all the sources under test will be measured and compared under very similar environmental conditions.

6.2.2 Radiated noise level

The Radiated Noise Level is a metric mostly used for describing the acoustic output of ships. The metric is calculated by correcting the measured data to account for spherical spreading from the source to receiver. It is a metric commonly used in ship noise characterisation and has been standardised both in the USA [ANSI 2009] and internationally [ISO17028-1 2011].

The calculation of Radiated Noise Level does not involve accounting for all the propagation phenomena in that it ignores the effect of the Lloyd's mirror caused by the refection of sound in the sea surface, though averaging the measurements made using hydrophones deployed at several depths is sometimes used to mitigate the effect. It also ignores the effect of absorption in the water (only important at the highest frequencies of interest for ship noise).

6.2.3 Source level

Background

Source level (or monopole source level) is a metric used frequently in underwater acoustics to describe the acoustic output of a source. It is a term not commonly seen in air acoustics where the acoustic power or energy is commonly used. In fact, the use of basic S.I. units to describe the "amount" of sound radiated from sources underwater would also be perfectly valid. If this is done, it is found that a merchant ship at modest speed radiates a few tens of watts of acoustic power into the water. For pulsed sources, it is more appropriate to describe the output in terms of energy, and for a typical acoustic positioning transponder (used routinely in the offshore industry) operating at mid tens of kilohertz, a single ping contains less than 1 joule of energy. However, for an airgun array used in geophysical surveying operating with a centre frequency of 50 Hz, the energy radiated per pulse is of the order of tens of kilojoules.

However, such S.I. units are rarely used to specify the acoustic output of underwater sources. Instead, the *source level* is used, a term originating from sonar engineering. Just as for power or energy, it may be considered as a characteristic property of the source that describes the acoustic output of the source itself, independent of the propagation path from source to receiver position. The Source Level may be related back to the acoustic power (or energy) of the source by use of knowledge of the acoustic impedance of the medium (this being the product of the medium density and sound speed).

Acoustic far-field

It should be noted that Source Level is an idealised acoustic far-field parameter and it only provides information about the sound levels in the acoustic far-field (it provides no information about the acoustic near-field). The value of the source level is perhaps best considered as the sound pressure that *would* exist at a *nominal* range of 1 m from the acoustic centre of an equivalent monopole source. Note that for a large distributed source such as a ship, a position 1 m away from the acoustic centre may be inside the ship itself.

Directivity

The source level describes the acoustic output *in a given direction*. For low enough frequencies, where the source is small with respect to the acoustic wavelength, the source will be omnidirectional. However, for acoustically large sources where the dimensions are many wavelengths across, the source level will show appreciable variation with angle.

Estimation of source level

In practice, for real sources, the Source Level is calculated by measuring an acoustic metric (such as sound pressure) at a distance from source which is in the acoustic far-field, in a specified direction, and propagating the value back to the reference distance of 1 m from the acoustic centre of the source using an appropriate propagation model. In this case, the acoustic propagation model must be able to account for all the propagation phenomena affecting the sound transmission such as spreading, absorption, reflection, refraction, and scattering (see Section 7.1).

Estimation of Source Level from sound pressure measurements in shallow reverberant channels is not straightforward since an estimate must be made of the true propagation loss, which is complicated by the interactions of sound with the seafloor and sea surface. This could be done with a sound propagation model which has accurate input data for all parameters (including the environmental parameters), but in practice this is often estimated empirically.

A point to note is that it is generally not possible to calculate the source level in shallow water by use of a simple spreading law such as $N.\log(R)$ to extrapolate back to the source (where N is often chosen from an empirical fit, or from experience is set to be equal to 15). The metric so obtained is a measure of the acoustic output of the source in that location, but is not a source level and cannot be used to predict the acoustic field of the source when placed in another location.

It is usual to express the source level for a broadband source as a source spectral level, expressed in third-octave band levels (or as a narrow band spectrum if examination of tonal components is required).

Types of Source Level and units

The source level is typically expressed in different ways depending on the source being characterised. This is unfortunate, and can easily lead to misunderstanding. The "type" of source level depends upon the metric used to measure the acoustic field at the position(s) in the acoustic far-field.

"Sonar" source level (often just called "source level")
This is calculated using the sound pressure level (SPL) and propagating the sound back to the reference distance of 1 m using an appropriate propagation model. Remember that the SPL is a time-averaged quantity (the root mean square sound pressure over a specified time duration). This is the type of source level most commonly encountered in the sonar engineering community, and is often referred to just as "source level" without qualification. This is most useful for continuous or quasi-continuous sound sources. The unit for source level (calculated from SPL) may be written as **dB re 1 μPa·m** (this mode of expression is correct in terms of the physical dimensions and conforms to the S.I. convention). However, in practice within the scientific field the unit is far more commonly seen expressed as **dB re 1 μPa at 1m**. This convention originates in the sonar engineering field and can appear confusing. This form of the unit may perhaps be more clearly understood as dB re 1 μPa *referred to* 1m. *Note that it does not necessarily equate to the SPL value measured at 1 m, nor does it imply that the measurements must be made at a range of 1 m*.

Peak pressure source level
Here the metric is the peak sound pressure (or sometimes the peak to peak sound pressure). Again the source level is calculated by back-propagation in the same way as described above. This is most often used when describing the output of airguns in the geophysical and seismic surveying industry. For peak pressure source level, the units may again be correctly written as **dB re 1 μPa·m**. However, in the geophysical surveying field, the acoustic output of airguns will sometimes be expressed in bar-metres. Note that one bar is equal to 100,000 Pa, or 220 dB re 1 μPa, so that a 100 bar-m airgun has a peak pressure source level of 260 dB re 1 μPa·m.

Energy source level
This is in some respects a misleading term in that it does not represent the energy output of the source in joules, but is calculated by back-propagation of the sound exposure level (SEL). It may therefore be thought of as the "SEL Source Level". It may be related to the energy flux density source level by knowledge of the medium acoustic impedance (if this energy flux were integrated over all directions, the total energy emission of the pulse could be found, and expressed in joules). It is used for impulsive or pulsed sources such as explosions, percussive marine pile driving and (on occasion) for airgun sources. It is also the source output metric specified in Descriptor 11, Indicator no. 11.1 of the Marine Strategy Framework Directive which deals with the distribution in time and place of loud, low and mid frequency impulsive sounds [European Commission 2010]. The units of energy source level are **dB re 1 $\mu Pa^2 \cdot m^2 \cdot s$**.

6.2.4 Difficult sources

Marine pile driving

It is not yet clear how to provide an entirely robust definition of source level for marine percussive pile driving. This is a source of some complexity, which penetrates both the water surface and the seabed, and where the source is not self-contained but is intimately connected to the environment. This means that if the environment changes, so does the source output. It is possible to calculate a type of energy source level from measurements made sufficiently far away for an individual piling scenario, and such metrics have been reported in the literature [Ainslie *et al* 2012, Robinson *et al* 2013]. However, the predictive utility of this metric is limited because when considering a different piling scenario, a number of the influencing factors governing the source output may well have changed. Examples of these factors include the water depth (exposing a different amount of the surface area of the pile), the seabed properties, the penetration depth into the seabed by the pile, the pile dimensions, and the hammer energy. Note that some of these factors may change during piling of an individual pile, for example hammer energy and sediment penetration, and this means that the acoustic output is likely to change during the driving of a specific pile.

Some encouraging efforts are being made to characterise the radiation by means of numerical models [Dahl *et al* 2010, Zampolli *et al* 2013] which have shown that the piling generates waves at specific angles to the vertical in the region close to the pile. Such efforts may lead to a better understanding of the dependencies of the acoustic output on the physical radiation mechanisms and the influencing factors described above. There is some experimental evidence of a linear dependence of acoustic output energy on hammer energy, but this is based on limited data [Robinson *et al* 2007 & 2013]. Until a validated physical model is available, when making estimates of source levels for future piling activity, it is advisable to base the estimate as far as possible on measurements made on piles driven under similar conditions (hammer energy, water depth, sediment type, etc).

Airguns and airgun arrays

Airguns are high-amplitude low-frequency pulsed sources used for geophysical surveying in hydrocarbon exploration. They are towed just below the water surface, such that the direct sound pulse and the pulse reflected from the water surface combine to produce a dipole source. Often, several airguns are towed together in the form of an array. The acoustic output of airgun arrays is widely reported in terms of the “far-field source signature”, which is the product of distance from the airgun array and far-field sound pressure at that distance (usually in the vertical direction, immediately beneath the array). The maximum magnitude of this product is sometimes termed the “source strength” [Johnson *et al* 1988]. This quantity is effectively the peak pressure dipole source level, with the dipole formed by the airgun array plus its surface image. Because the strength of an airgun array is specified in terms of peak sound pressure and because peak pressure is sensitive to bandwidth, it becomes necessary to specify a frequency band. Much of the energy from airguns is directed downwards, and therefore directivity data are needed to assess their significance. Directivity plots are routinely produced by seismic survey companies in advance of carrying out their surveys [Johnson *et al* 1988].

6.3 Measurement

6.3.1 Temporal sampling

To characterise the source output as a function of time, measurements need to be undertaken for an extended period which covers the expected output variation of the source. This is best undertaken with an autonomous recorder at a fixed range from the source for the duration of the measurements. Examples of where the use of such a method is useful are:

- to measure the source output variation during marine pile driving [Robinson *et al* 2013]. The variation could be due to tidal changes, increased seabed penetration, or hammer energy increase during the soft start period. A measuring buoy should be placed at a fixed location and used to measure the entire piling sequence;
- to measure the operational noise of an offshore windfarm, where the radiated noise within the windfarm should be monitored during all prevailing wind conditions using a fixed deployment;
- to measure a wave or tidal stream energy device where the noise output depends on the operational conditions (this requires close co-operation with the device operator).

6.3.2 Spatial sampling

In order to empirically determine the propagation loss for deriving the source level of the source, measurements may be made as a function of range from the source [Nedwell *et al* 2007b, De Jong and Ainslie 2008, Robinson *et al* 2013]. This is particularly beneficial for measurements in shallow water where it would be difficult to obtain high accuracy with a purely theoretical model.

The procedure can be expedited in one of two ways:

(i) a mobile measurement platform such as small vessel is used for the measurements, and while the source is operational, the vessel moves along a linear transect away from the source, stopping to measure at a number of ranges from the source;

(ii) a series of recorders are stationed along a linear transect from the source and these recorders measure the radiated noise along the transect simultaneously.

In option (i), it is important to also measure using a recorder at a fixed location so that any temporal variation in the source output is also measured. Option (ii) is superior in that the output is measured at all stations simultaneously, but the cost of multiple recorders may be prohibitive (and it is unlikely that as many locations could be sampled as are possible with option (i)). Note that for option (i), if the source output varies with time, there may be a need to correct the results to account for this variation *before* calculation of the source level. Thus, a combination of option (i) and (ii) are preferable in this instance.

In the calculation of the source level, an appropriate propagation model can be fitted to the measured data as a function of range, or each station’s data can be used to calculate a source level, and the resulting source level data may then be averaged.

Figures 6.1, 6.2 and 6.3 show examples of possible measurement configurations for different types of source, showing the use of both fixed and mobile deployment platforms. Figure 6.1 shows a possible deployment configuration for measuring the radiated noise in shallow water with a static recorder at a fixed location and a mobile vessel moving along a linear transect away from the source, which in this example is marine percussive piling for offshore construction.

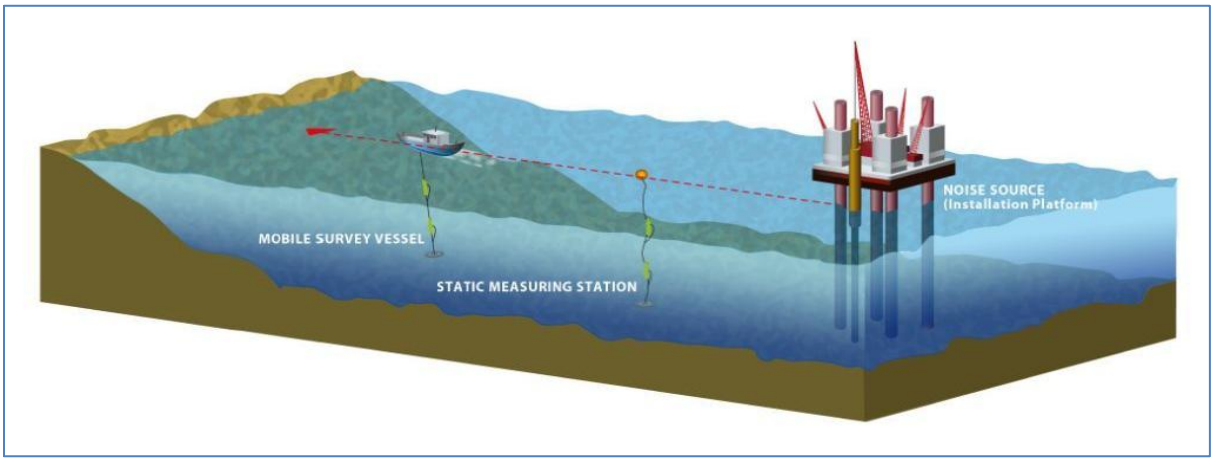

Figure 6.1: Possible deployment configuration for measuring the radiated noise in shallow water, with a static recorder and a vessel for range-dependent deployments along a transect.

Figure 6.2 illustrates a potential configuration for shallow water using a series of fixed recorders located at positions along a transect. In the example shown, the source is a vessel. Note that the measurement stations may be either recorders or hydrophones deployed from a vessel which is anchored (as shown for one of the measuring stations in Figure 6.2).

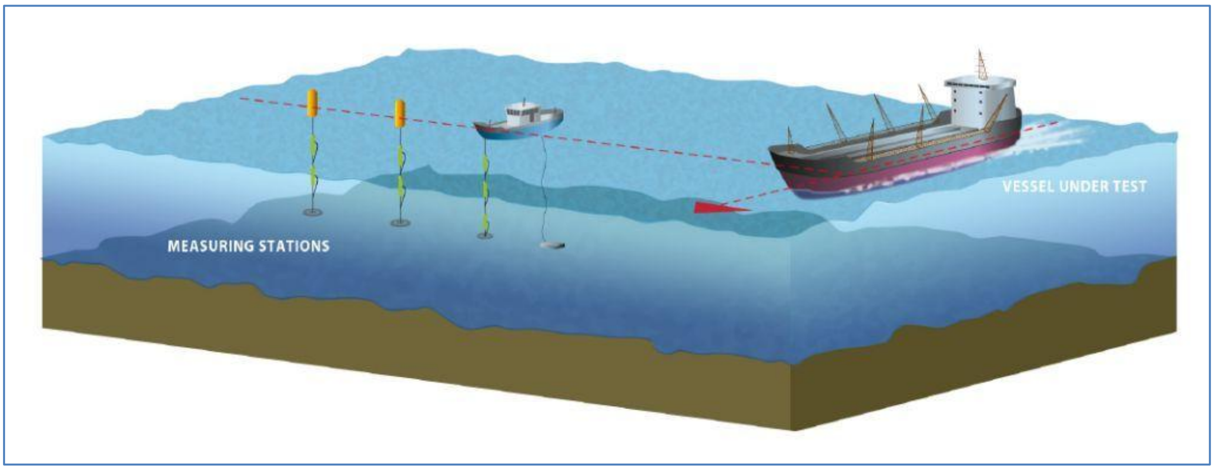

Figure 6.2: Possible deployment configuration for measuring the radiated noise in shallow water, with a series of fixed recording stations located at positions along a transect.

Figure 6.3 shows a possible measurement configuration for measurement of a vessel in deeper water. Here, three hydrophones are deployed from the surface (these are shown to be deployed from a measuring buoy but could equally be from a vessel). If the hydrophones are to be used to undertake the measurements required by ISO 17028 and ANSI S12.64, the hydrophones should be deployed at specific “look-down” angles, and resulting hydrophone data are averaged to provide a measure of the Radiated Noise Level [ANSI S12.64 2009, ISO 17028 2012]. Note that the diagram is not to scale (the distance at closest point of approach is typically about 100 m).

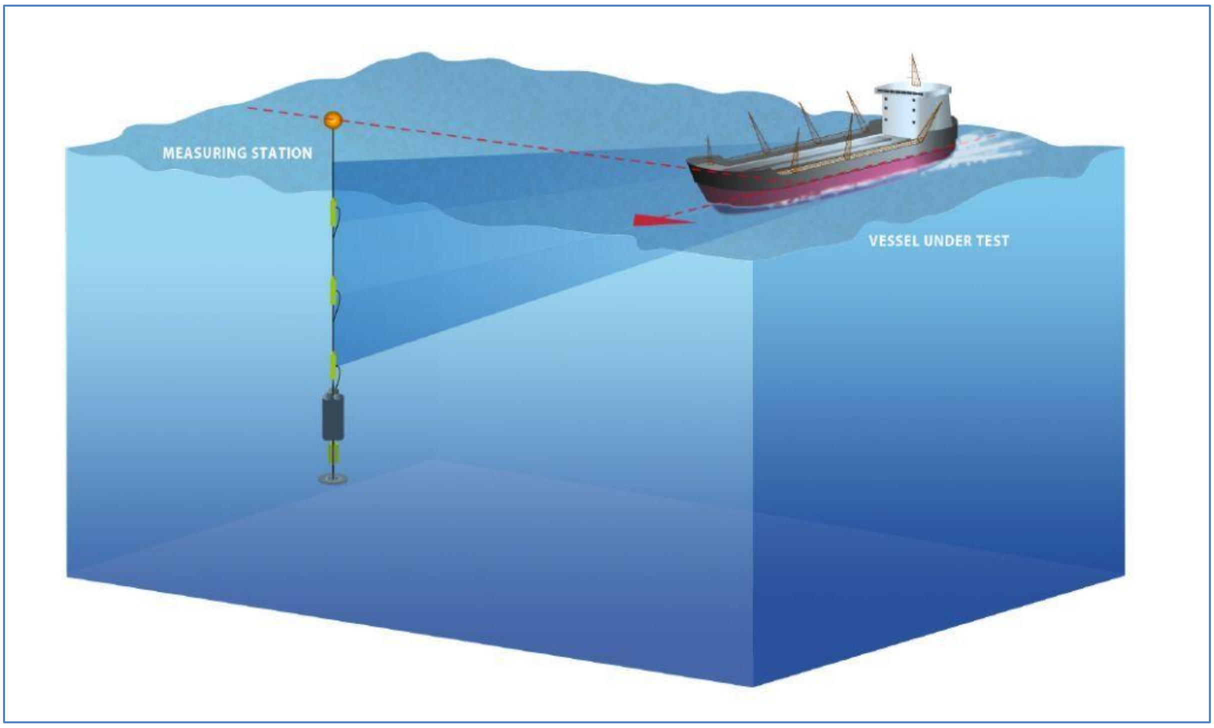

Figure 6.3: Possible deployment configuration for measuring the radiated noise in deeper water, with a hydrophones and recorder deployed from the surface. Note that the diagram is not to scale.

6.3.3 Engineering measurements of radiated noise

In addition to environmental concerns, another motivation for measuring (and wanting to minimise) radiated acoustic noise is when such noise interferes with the operation of acoustic systems. This is particularly true where the systems are deployed on noisy platforms where there might be an individual source of noise; an example might be the thrusters on a dynamically-positioned vessel. In such cases, it is not always practical or convenient to deploy remote hydrophones or recorders in order to determine the levels of radiated noise. In some of these cases, indicative values may be obtained by quite simple measurements where the hydrophones are deployed from the vessel itself but at some distance from the source and on long cables to provide sufficient depth.

For a large vessel or platform, such as a dynamically-positioned vessel or crane barge, the vessel dimensions may be greater than 200 m, and it is possible to deploy hydrophones from a remote part of the vessel away from the source under consideration. For such measurements to be successful in deriving a radiated noise level or source level, it must be possible to attain far-field conditions and this may only be possible for low frequency sources of noise. It is also necessary to have a reasonably accurate estimate of the source-hydrophone distance, and the source under study must dominate (such that other sources contribute little to the noise signal). Although these are challenging criteria, there are still merits in taking such measurements to check the effects of this noise on the operation of other acoustic systems.

6.3.4 Measurements in reverberant tanks

For small sources (or small noisy components), it is possible to make measurements of radiated noise in reverberant tanks. An example of relevance to the offshore industry is the noise produced by remotely operated vehicles (ROVs), where the noise produced by the vehicles may limit the performance of acoustic systems mounted on them (for example, acoustic positioning transponders). The self-noise of the ROV can be high, and may have specific components which are very noisy (such as hydraulically-operated pumps). Hydrophone measurements may be made with the ROV deployed in a tank which is large enough and reverberant enough that the reverberant field dominates the acoustic field within the tank, except for the region close to the source [Cochard *et al* 2000, Hazelwood and Robinson 1998]. This is analogous to the methods used in air acoustics to measure sound power of sources in reverberation chambers [Blake and Maga 1975]. The tank may have to be first "calibrated" to determine its absorption, either by measuring the reverberation time or by use of a calibrated projector as a source. This method cannot provide any directional information about the noise source.

6.3.5 Calibrated source used as a reference device

As an alternative method for empirically determining the propagation loss, instead of spatial sampling along a linear transect (as described in Section 6.3.2), a calibrated source may be used to "calibrate" the environment. Here, a calibrated source which operates over the same frequency range as the source under test is deployed in the test area and measured by the recording system. Because the source has previously been calibrated, the difference between the measured value of source level and the true value as a function of frequency may be determined for the calibrated source. These differences are then applied as a correction when measuring the unknown source under test.

This method only works if the calibrated source can replicate the performance of the source under test reasonably well. For large mechanical sources, this is not an easy task. The technique has mostly been used for measurement of ship noise, but even in this case it is not easy to design a source which is a good representation of a ship.

6.3.6 Frequency range

The frequency range over which measurements are made will depend on the objective of the measurements. For example, if the purpose is related to the potential for impact on marine species, the frequency range of hearing of the marine receptors may govern the frequency range of the measurements. In UK waters this may cover frequencies from a few tens of hertz for some fish species, to high frequency cetaceans such as the harbour porpoise with frequencies in excess of 150 kHz. If the objective is to characterise the source output, the measurements need cover only the frequencies radiated by the source. However, the frequency range of the radiated noise may not be known a priori, and it should be borne in mind that there may occasionally be unexpected high frequency components.

Note that criteria stated in Section 3.1.2 apply, for example with regard to sampling frequency for ADCs.

6.3.7 Equipment and deployment requirements

The key performance criteria for equipment, instrumentation and deployment are listed in detail in Section 3 and Section 4. For measurements of radiated noise, the following are of particular importance:

- **Sensitivity**: in general, the sensitivity of the system should not be too high if the source is high amplitude in case of saturation and clipping (Section 3.1.1),
- **Dynamic range**: the dynamic range should be sufficient to record all signals without distortion or clipping (Section 3.1.5)
- **Calibration:** the recording system must be calibrated before deployment ove the frequency range of interest (Section 3.2);
- **Data storage**: see Section 3.3;
- **Platform noise**: steps should be taken to minimise noise from deployment platforms, particularly for low amplitude sources (Section 4.3)
- **Self-noise**: a low self-noise system should be used for measuring low output sources (Section 3.1.4);
- **Auxiliary data**: important to record metadata so that noise levels may be correlated with environmental data (eg weather) or ship traffic data (see Section 4.4);
- **Protection from loss/damage**: an important topic to safeguard data in long-term deployments (Section 4.5).

6.3.8 Contamination by additional noise sources

In-situ measurements of ocean noise are not made under controlled conditions. In some circumstances, the measurement of radiated noise may be contaminated by additional noise sources such as other vessels, Acoustic Deterrent Devices from local aquaculture sites, other construction noise, geophysical surveying activity. This problem is most severe for sources that are not themselves of high source level, such as operational noise from offshore renewables. In these cases, the noise from other local sources, such as vessels, may dominate the soundscape. If some of the anthropogenic sources are semi-permanent, they may be regarded as part of the soundscape of the area. However, where possible, attempts should be made to measure when the contaminating sources are absent.

Summary: Radiated noise measurement

Ensure that the objectives of the measurements are clear and that the measurement configuration is appropriate for those objectives (6.1 & 6.2).

Ensure that the source output metrics are appropriate for the objectives, and that the measurement configuration enables the chosen metrics to be derived (6.2).

If a source level is calculated, ensure that an appropriate propagation model is used which accounts for the relevant physical propagation phenomena (6.2.3).

Ensure that the measurements satisfy the requirements of the objectives such that:

- the instrumentation is correctly specified for the application in terms of frequency range, dynamic range and self-noise (6.3.6, 6.3.7);
- spatial sampling is appropriate to ensure far-field conditions (6.1.4) and (if required) to provide an empirical check on propagation (6.3.2);
- the temporal sampling captures any variation in acoustic output using a fixed (static) recording position (6.3.1);
- the deployment minimises measurement artefacts and parasitic signals (6.3.7);
- contaminating noise sources are minimised (or eliminated) (6.3.8).

7. Choice of propagation models

7.1 Background

The ocean environment is a complex one, and there are many factors that influence the propagation of sound. Although a full discussion of the topic is beyond the scope of these guidelines, some understanding of the physical principles involved is of benefit.

Note that the best validation of an acoustic propagation model is by comparison with empirical data from measurements of transmission loss. If such measurements are available for some locations and scenarios, a direct comparison of model predictions with measured data will indicate the likely accuracy, and provide confidence in model predictions for which there are no measured data.

7.1.1 Factors affecting sound propagation

There are a number of factors that influence the propagation of sound in the ocean and contribute to the propagation loss (the reduction in signal as sound propagates from source to receiver) [Jensen *et al* 2000]. Broadly, these include the following:

- The geometrical spreading of the sound away from the source;
- Absorption of the sound by the sea-water and the sea-bed;
- The interaction with the sea-surface (reflection and scattering);
- The interaction with (and transmission through) the sea-bed;
- The refraction of the sound due to the sound speed gradient;
- The bathymetry (water depth) between source and receiver positions;
- Source and receiver depth.

A number of the above factors depend on the acoustic frequency, and a complex model will include frequency dependence explicitly within the model parameters.

An important influence is the speed of sound, which can vary with depth strongly, especially where the water is deep. The sound speed profile may be divided into several layers: a surface layer where the speed is susceptible to daily changes due to heating, cooling and wind action; a seasonal thermocline, a region characterised by a negative sound speed gradient due to the decrease in temperature with depth; and a deep isothermal layer, which is roughly constant in temperature and where the sound speed increases with depth due to the increasing hydrostatic pressure. Between the thermocline and the isothermal layer is a sound speed minimum, toward which sound tends to be bent by the action of refraction. Some of the sound from a source placed in this channel can be trapped by the action of refraction within the channel and travel great distances without suffering significant losses caused by surface or bottom reflections. The variation with salinity is less of an influence in deep water, but can have a strong influence where water layers of different salinity are mixing, for example at the estuaries of fresh-water rivers.

In shallow water around the UK coast, the sound speed is less likely to vary strongly with depth due to the shallow conditions and the often rapid tidal flow, which often leads to a mixed isothermal water column.

The sound speed is such an important oceanographic parameter that it is routinely measured as a function of depth, either directly using a velocimeter, or indirectly calculated using measurements conductivity (to derive salinity), temperature and depth using a CTD meter, with the sound speed calculated from empirically-derived relationships. Guidance on calculation of sound speed in the ocean (including an interactive calculator) can be found at:
http://resource.npl.co.uk/acoustics/techguides/soundseawater/

The absorption of sound in seawater is caused by both viscous losses and a number of chemical relaxation processes due to dissolved salts. The absorption depends on the seawater properties, such as temperature, salinity and acidity, and increases with frequency such that high frequency sound will travel much shorter distances before being reduced to the level of the background noise. Guidance on calculation of sound absorption in the ocean (including interactive calculator) can be found at: http://resource.npl.co.uk/acoustics/techguides/seaabsorption/

7.1.2 Shallow water propagation

In shallow water, the interaction with the seabed and sea surface becomes very important. The surface and seabed act as boundaries which “channel” the sound between them with the action of a waveguide. Figure 7.1 illustrates this effect schematically.

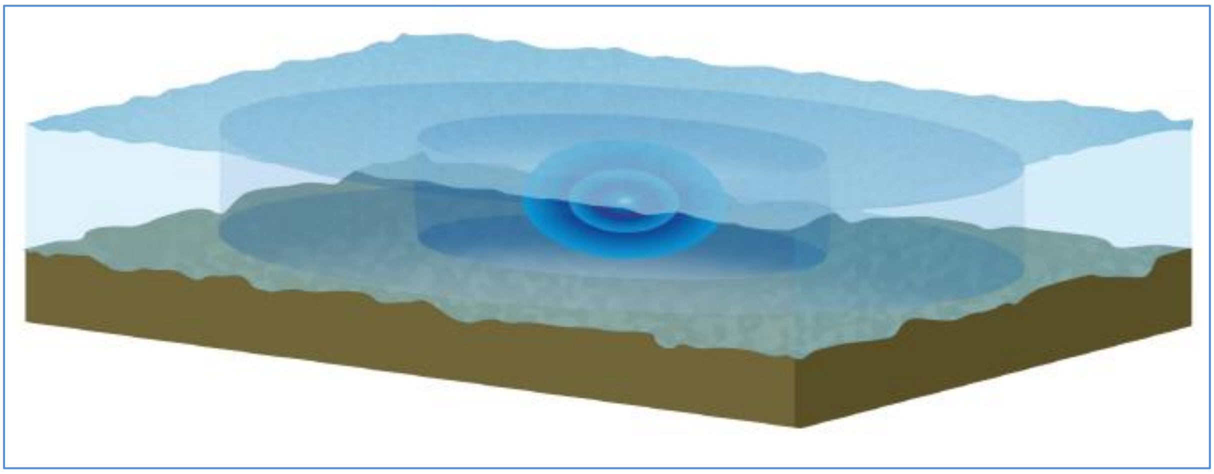

Fig 7.1: The propagation of sound in a shallow water channel, showing schematically the interaction with the medium boundaries.

Note that the water-air interface is a “pressure-release” boundary, and cannot support an acoustic pressure (the surface is free to move). Therefore, close to the surface, the sound pressure approaches a zero value (whereas the sound particle velocity is high).

One effect not always appreciated is that shallow water channels do not allow the propagation of low frequency signals due to the wave-guide effect of the channel [Urick 1983, Clay and Medwin 1977, Jensen *et al*. 2000, Ainslie 2011]. This effect means that there will be a lower cut-off frequency, below which sound waves will not propagate well. The cut off frequency of the lowest mode in a channel of depth, *H*, is given by:

$$f_0 = \frac{c_0}{4\,H\ \sin\theta_c}$$

where c_0 is the sound speed in water, and θ_c is the critical angle, which is given by:

$$\theta_c = \cos^{-1}\frac{c_0}{c_1}$$

where c_1 is the sound speed in the sediment [Clay and Medwin 1977]. Any sound at frequencies below the cut off will not be able to propagate far in the channel because the grazing angle of the sound wave exceeds the critical angle and it losses energy very quickly through multiple reflections between the surface and bottom. The cut-off frequency as a function of water depth is shown in Figure 7.2.

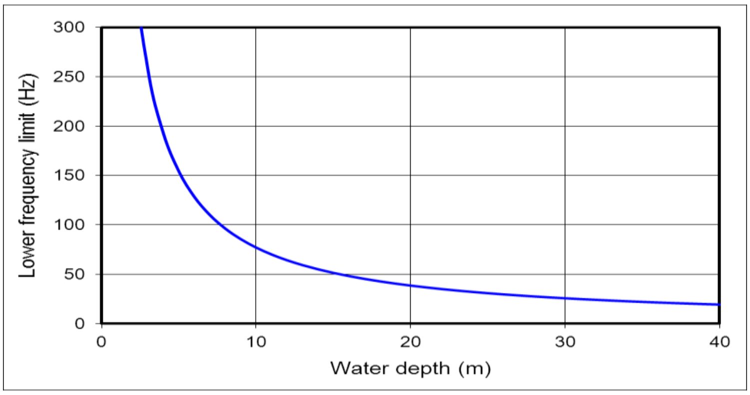

Fig 7.2: The lower cut-off frequency as a function of depth for a shallow water channel with a seabed sound speed of 1702 m/s (sand) and water sound speed of 1490 m/s.

7.1.3 Full acoustic models

The wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations. However, much has been achieved in this field, and it is possible to make accurate estimates of the propagation of sound if sufficient information is available about the environment. A sophisticated model will make use of information about the water column itself (sound speed profile, absorption, bathymetry), seabed (sound speed, density, absorption), sea surface (roughness, bubble presence) and the depths of source and receiver.

Models are generally categorised as range independent (the input parameters are kept fixed), and range dependent (input parameters such as water depth and sound speed are allowed to vary with range from the source), the latter being the preferred choice when the bathymetry or water column conditions change along the propagation path. There are a wide variety of models available, some of which are available to download free of charge, but these complex models require some expertise to run them successfully. The models may be categorised generally into a number of classes [Jensen *et al* 2000, Weston 1976]:

- Ray tracing models
- Normal mode models
- Parabolic equation model
- Wavenumber integration models
- Energy flux models

Note that although in principle it is possible to model vector field quantities such as sound particle velocity, in practice this is rarely done, and most modelling is used to predict the transmission of sound energy, sound intensity or sound pressure.

7.1.4 Semi-empirical models

In some cases, empirically-based models have been set up using measurements of propagation loss made in specific locations. For example, Marsh and Schulkin presented a semi-empirical propagation model that can be used in a water channel with known depth, including the effect of frequency-dependent absorption [Marsh and Schulkin 1962]. The model can be extended to include effects such as surface scattering and sound speed gradients, and has been validated by comparison with experimental data.

Based on measurements made over a number of years, Thiele developed an algebraic formula that is applicable for coastal North Sea and Baltic waters with water depths up to 100 m, a sandy bottom and wind-speeds of less than 20 knots [Thiele 2002]. The model is range independent, and it is reduced to a power spreading law with *N*=16 at low frequencies.

7.1.5 Simple models

In some cases, acceptable accuracy for some purposes may be obtained by use of relatively simple models. Commonly used models include those based on spreading laws such as spherical spreading (in decibel notation, this corresponds to a reduction in received level with range, *R*, of "20.log(*R*)"), or cylindrical spreading in shallow water (corresponding to a reduction in received level with range of "10.log(*R*)"). In practice, the spreading may lie somewhere between these two geometries and be described by "*N*.log(*R*)" where *N* typically has a value between 10 and 20.

Such simple models do not include any frequency dependence or bathymetry dependence or the effect of absorption in the medium, though this may be included in a simplified manner by introducing extra terms.

Such simple models may be used to interpolate the propagation loss between two ranges in the far-field of the source. However, the limitations of these models should be considered carefully. Such a model does not account for changes in bathymetry, and so cannot (for example) predict the extra reductions in level caused by sand banks and shallow coastal areas. In addition, such models do not generally include frequency dependence explicitly, and so cannot predict the increased loss at high frequencies due to increased sound absorption.

Care should also be taken when applying propagation models to time-domain metrics such as peak sound pressure and peak-to-peak sound pressure. Most propagation models are intended for use in calculating loss in energy or a time-averaged quantity such as sound pressure level, and are not so robust when predicting the propagation loss for peak sound pressure. Although it is possible to model the propagation of a time domain waveform using finite difference techniques, or by calculation of a frequency domain transfer function and using deconvolution methods, in practice this is requires sophisticated approaches which are time and computationally intensive.

The transmission of sound in shallow water will show a strong dependence on frequency due to the modal nature of the propagation and the frequency-dependent absorption in the water and in the sediment. These phenomena will cause the time waveform to distort during propagation away from the source, typically causing a dilation of the acoustic pulse (an increase in pulse duration) and a reduction in high frequency content.

7.1.6 Broadband propagation

For propagating broadband signals, for example within specific third-octave frequency bands, a propagation model may be required that accounts for the range of frequencies within the band. Many models run in the frequency domain, producing propagation loss data for single frequency excitation that exhibit strong amplitude fluctuations due to the coherent interference effects. For a broadband signal, an average of the propagation loss for the entire frequency band is required (this is likely to exhibit much smoother spatial variation than for individual frequencies within the band). This can be achieved by running a model at a number of frequencies within the band and averaging the results, or by performing an equivalent averaging process as a function of range [Harrison and Harrison 1995].

7.2 Source representation

Most propagation models make simplifying assumptions about the nature of the source; for example, that is it behaving as a monopole point source. These simplifying assumptions are often necessary to make the computational problem tractable. Most sources are not point sources but are distributed sources of sound. However, most sources will approximate to point sources when observed from great distance (where all the sound waves appear to diverge from an “acoustic centre”). Thus, for many sources where predictions are required for considerable range, the simplifications do not invalidate the modelling process.

However, this means that such acoustic modelling will only be capable of predicting the sound field in the acoustic far-field, and will be incapable of predicting the acoustic near-field region close to the source. For predictions close to the source, a much more complex representation of the source is required. Accurate predictions may require the use of a distributed physical model such as a finite element model.

7.3 Uses for propagation models

There are a number of uses for propagation models in connection with the measurement and prediction of sound in the ocean.

7.3.1 Interpolation of measured data in the acoustic far-field

Here, the desire is to interpolate between measured data in the acoustic far-field of a source. If the measured data are relatively close together in range, and there are no significant bathymetric features between the measurement locations, a simple spreading law model will suffice and provide reasonable accuracy, especially if the parameters of the model are derived empirically.

7.3.2 Extrapolation of measured data to greater range from the source

Here, simple models also can have some utility. However, care must be taken in using simple models if the extrapolation is over a significantly extended range. For example, if broadband signals are being propagated, the frequency dependence of the propagation must be accounted for (higher frequencies will be more strongly attenuated by absorption). If the bathymetry varies by a significant fraction of the water column over the extrapolated region, the model must include depth dependence for accurate prediction.

7.3.3 Derivation of source level

In this case, the propagation model is used to propagate the measured data back to the source to derive a value for source level. If extrapolation over a significant range is required, the considerations stated in the above sections apply here also with regard to frequency dependence and bathymetric dependence.

However, another aspect to consider is that simple spreading models such as N.log(R) cannot be used to derive a monopole source level (unless the value of N is 20, as would be the case in very deep water where the effects of boundaries are negligible).

In shallow water, when propagating back to the source using such a model, in order to account for the propagation close to the source itself a constant term must be added (a term which includes the water depth at the source position) [Kinsler *et al* 2000]. In such cases, it is preferable to use a model that can account for all the propagation phenomena in calculating a source level. Ideally, the broadband source level is calculated as a sum of contributions from frequency bands, each of which may be propagated individually.

7.3.4 Production of a noise map

Propagation models are sometimes required to produce a noise map of the region around a source. This requires that the source level be available in a suitable form to use as an input to the model (this is most often in the form of a monopole source level).

Production of a noise map is often required over large ranges (sometimes tens of kilometres). The model used will need to have the capability to cope with varying bathymetry over quite a long range, and frequency dependence if the signals are broadband. Speed of computation may also be a requirement for coverage of large areas.

In underwater propagation modelling, although it is possible to obtain good resolution in range from the source and depth in the water column, the models are not usually fully three-dimensional, but are instead formed of a series of two-dimensional slices through the water column (range versus depth) at a succession of bearings. There are very few models that can cope with horizontal spreading due to refraction, diffraction or reflection, and none that are readily available. This means that noise maps can exhibit “shadow zones” where the modelled sound cannot penetrate behind obstacles such as small islands.

When producing a noise map, consideration needs to be given to the process of gridding the data in terms of spatial resolution. This may be influenced by the resolution in the available bathymetric data. A decision must be made as to whether the model produces data which are resolved in terms of water depth (such that the acoustic field variation with depth may be calculated), or whether the average of the sound energy with depth is calculated (as produced by an energy flux approach). The former requires far more intensive computation. In the azimuthal direction (the plane of the water surface), the grid is typically Cartesian with data calculated for each node in the grid. A grid based on radial transects will suffer decreasing spatial resolution at increasing range from the source. Any interpolation undertaken as part of the mapping should be made clear.

7.4 Criteria in choosing a model

It is not appropriate here to recommend specific models since in many cases there can be a number of different potential solutions that are equally accurate [Etter 2013]. In choosing the propagation model, it is important to ensure it is fit for purpose and suited to the task at hand. Annex B (Section 11) of this guide provides a listing of web-sites where modelling software may be downloaded, and where input environmental data may be sourced. The following criteria may be used to determine the suitability of a propagation model.

Range dependent bathymetry (and sound speed)
If the model is being used to propagate sound over significantly changing bathymetry, is the model capable of accounting for the change in propagation conditions encountered? Is depth dependence explicitly included in the model? Is the model capable of accounting for the low frequency cut-off in shallow water? Does the model take account of sound speed variations (particularly important for deeper water)?

Frequency dependence for broadband signals
When propagating broadband sound over considerable distance, the frequency dependence of the absorption will significantly affect the loss. Is the model capable of coping with frequency dependence in the propagation?

Interaction with medium boundaries

The model should account for the interaction with the medium boundaries. This includes both reflection and transmission of sound at the seabed, and potentially transmission of sound through the seabed (including the transmission of shear waves). The reflection at the air-water surface may also depend on surface roughness (especially for frequencies greater than 1 kHz).

Benchmarking

Many of the freely available models developed by acoustic oceanographers have been extensively benchmarked. This provides confidence in the model accuracy (though it may still require expertise to use the model effectively). A model that has been written in-house should ideally be benchmarked against another model or against experimental data to validate it.

Agreement with experimental data

If the model predictions can be compared with experimental data to obtain good agreement within the uncertainties, this provides considerable extra confidence in the model. For example, in cases where experimental data are available, the model should provide a good fit to the measured data over the range of distances from the source that measurements are available. Agreement with experimental data are the most significant validation for any propagation model (assuming that the experimental data are accurate).

Summary: Propagation modelling

Ensure that the choice of model is appropriate for the application (7.3).

Ensure that the propagation model used accounts for the physical propagation phenomena relevant to the scenario, including the following potential influencing factors (7.4):

- range-dependent bathymetry including dependence on varying water depth and the frequency cut-off for the channel;
- sound speed including the sound speed profile (especially for deeper water);
- frequency dependence, including absorption in the water;
- seabed properties, including propagation within the seabed;
- interaction with the sea surface, including the effect of surface roughness.

Preferably, use a model that has been benchmarked against historical experimental data or by comparison with other propagation models, or check consistency with range-dependent measured data from current experimental work (for example, when measuring radiated noise).

8. Uncertainties

8.1 Introduction to uncertainty

The value of a measurement is extremely limited without some estimation of the uncertainty. The uncertainty is an estimate of the range of values within which the true value is considered to lie to a specified degree of confidence (for example, for a confidence level of 95%). Analysis of uncertainty is a well-established discipline with standard procedures, for example the international Guide to the Expression of Uncertainty in Measurement [GUM 2008].

Note that uncertainty estimation should be distinguished from the natural variation in the measured quantity that might occur due to the fact that the quantity itself is changing over time. For example, the level of ambient noise will vary with sea-state, and the noise radiated by a vessel may vary depending on the speed and engine loading, and the noise radiated during a marine piling operation may vary during a soft start where the hammer energy is increasing gradually.

When measuring underwater noise, there are potentially large sources of uncertainty which are difficult to quantify. This can make it very difficult to ascribe uncertainty values to the results (often these are displayed in the form of “error bars”). However, it is valuable to consider the sources of uncertainty and attempt to make some evaluations so that bounds may be placed upon the results.

There are two general classes of uncertainty. Type A uncertainty is sometimes described as the “random uncertainty” or repeatability, and may be assessed by making related measurements of a quantity and examining the statistical spread in the results. It may not be possible to make repeated measurements if the event being measured is unique (for example, an explosion as a source of sound). However, for some measurements (for example, the noise ranging of a vessel), it is feasible to make repeated measurements (for example, for repeated passes of the vessel under test). The Type A uncertainty is a measure of the precision in the measurement – high precision is obtained if the measurements are repeatable with little dispersion in results.

The second category is the Type B uncertainty, which is sometimes referred to as the “systematic uncertainty”, and represents the potential for systematic bias in a measurement (for example caused by incorrect instrument calibration). This category of uncertainty cannot be assessed using repeated measurements, and must be evaluated by consideration of the potential influencing factors on the measurement accuracy.

8.2 Sources of uncertainty

Uncertainty in the calibration of instrumentation

Uncertainty in the calibration of instrumentation will contribute to the overall uncertainty. It is possible to calibrate a hydrophone in laboratory conditions with an uncertainty of 0.5 dB, and the overall uncertainty of the recording system can be of the order of 1 dB. However, consideration should be given to the factors described in Section 3 which can cause the uncertainty to be degraded. Uncertainties introduced by instrumentation can be significant; for example, an uncalibrated preamplifier with a 10 dB offset will cause every measurement to be in error by this factor (an example of systematic bias or Type B uncertainty).

Uncertainty in the position of source and receiver

For measurements in the ocean, it is not a trivial matter to achieve high positional accuracy. In measurement of radiated noise from a source, use of GPS or laser range finding equipment can provide extra confidence, but residual uncertainty is inevitable. The relative uncertainty is likely to be greater if the source-receiver ranges are short: a fixed 10 m error equates to a 10% error in a range of 100 m, but a 0.1% error in arrange of 10 km.

Spurious signals introduced by the deployment

Although every attempt should be made to eliminate sources of spurious signals such as those identified in Section 4, this is not always possible. Estimates should be made of any residual effects for inclusion in the uncertainty analysis.

Validity of any assumptions made

Any assumptions made about the sound field should be reported and validated. For example, if an assumption is made about the propagation of the sound field, or about the existence of far-field conditions, this should be made explicit and if possible an uncertainty should be assigned to it.

Uncertainties in any input parameters in a propagation model

The input parameters to any propagation model will not be known exactly. Examples include the seabed properties, the sea surface roughness and the sound speed profile. One method to assess the effect of these uncertainties is evaluate the model for a range of values of the input parameters and examine the variation in the results (sometimes termed a “sensitivity” analysis).

8.3 Evaluating uncertainty

When evaluating uncertainty, there are a number of steps recommended:

- Check for any spurious artefacts and eliminate spurious signals – try 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 or 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 – this 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 Guide to the Expression of Uncertainty in Measurement [GUM 2008].

An example where there is significant natural variation might be ambient noise, where the natural variations may be tens of decibels – much greater than the measurement uncertainty for any one measurement. Similarly, the radiated noise from some sources may vary significantly with environmental conditions by an amount which is likely to be far greater than the measurement uncertainty (for example, the operational noise of marine renewable energy devices).

Summary: Uncertainties

All measurements require an estimate of uncertainty in order to be useful.

Uncertainties may be categorised into two classes (8.1):

- Type A: a measure of the repeatability of the measurement (derived from the statistical dispersion of repeated measurements);
- Type B: a measure of uncertainty due to any the systematic bias.

There are a number of potential sources of uncertainty (8.2):

- calibration of instrumentation;
- position of source and receiver;
- spurious signals introduced by the deployment
- validity of any assumptions made;
- environmental parameters (for use in a propagation model).

Uncertainties may be evaluated by following the international Guide to the Expression of Uncertainty in Measurement (8.3)

Measurement uncertainties are an attempt to quantify how accurately we are able to measure a quantity, and should not be confused with natural fluctuations and variability in a quantity (for example, the potentially large variations in ambient noise due to changes in weather, etc).

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10. Annex A: Glossary

acoustic	a synonym for “sound”, as in acoustic pressure or sound pressure
ADC	Analogue to Digital Converter – a signal processing device that converts analogue signals into digital representations
ambient noise	acoustic signals originating from sources other than the source of interest; the acoustic noise in the absence of the source under investigation; sometimes called “background noise”; see definition(s) in Section 5
ANSI	America National Standards Institute (US standards body producing written specification standards)
background noise	acoustic signals originating from sources other than the source of interest; the acoustic noise in the absence of the source under investigation; sometimes as a synonym for “ambient noise”
BIPM	Bureau des Poids et Mesures (Bureau of Weights and Measures); an intergovernmental organisation through which Member States act together on matters related to measurement science and measurement standards; based in Paris
BSI	British Standards Institute (UK standards body producing written specification standards)
calibration	a measurement which established the relation between the input quantity and indicated output quantity for an instrument
dB	decibel; a logarithmic unit expressing the level of a quantity; equal to $10.\log_{10}(a_1^2/a_0^2)$, which is mathematically equivalent to $20.\log_{10}(a_1/a_0)$, where a_1 is the absolute value of the field quantity and a_0 is the reference value of that quantity
drilling	a method of installing a structure on the seabed where a drill is used to create a hole or socket for the structure (eg a pile); an installation technique commonly used for hard seabed or sediment (rock or compacted chalk);
EU TSG Noise	Technical Sub-Group on Noise; EU convened expert group providing advice on implementation of the EU MSFD Descriptor no. 11 on underwater noise
frequency	the “pitch”, or number of oscillations per second of a sound wave
IEC	International Electrotechnical Commission. International standards body producing written specification standards on electrical measurements and instrument calibration.
ISO	International Organisation for Standardisation. International standards body producing written specification standards, including on physical measurements
high pass filter	An electronic filter which passes high frequency signals, but attenuates low frequency signals (frequencies lower than the specified cut-off frequency)
hydrophone	transducer which converts acoustic signals into electrical signals; analogous to an underwater microphone; transduction is often based on the piezoelectric effect
low pass filters	An electronic filter which passes low frequency signals, but attenuates high frequency signals (frequencies greater than the specified cut-off frequency)
MEDIN	Marine Environmental Data and Information Network
medium	substance which supports elastic and acoustic waves, and through which sound waves travel; can be a fluid (water or air), or a solid material
MSFD	EU Marine Strategy Framework Directive
monopole	a point acoustic source which has an omni-directional acoustic output (the acoustic energy is radiated in all directions equally)
noise	unwanted signal (sound) received by a receptor
Nyquist frequency	0.5 times the sampling frequency of a digital signal processing system
piling	the installation of a pile into the seabed; may be achieved by percussive piling using a hammer (marine impact pile driving), or by drilling, or by vibro-piling;
percussive piling	marine pile driving where the pile is driven into the seabed using a succession of blows with a hammer; often called marine impact piling; a high amplitude low-frequency source of sound;
quantisation	The noise due to rounding or truncation error introduced in the digitisation of small

noise	amplitude signals due to the finite resolution if the ADC
Propagation Loss (PL)	reduction of sound level with range from the source, expressed in decibels;
radiated noise	the acoustic noise radiated by a specific source of interest
RL	Received Level; see definition in Section 2
RMS	Root mean squared quantity; a time-averaged quantity where the amplitude is first squared, then averaged over a specified time interval, then square-rooted to derive the final RMS value
Radiated Noise Level (RNL)	a sound output metric describing a source; calculated from the received level corrected for propagation between source and receiver by use of a simple spherical spreading model of the type $20.\log_{10}(R)$; commonly used to express the acoustic output of ships in deep water; see definition in Section 6
SEL	Sound Exposure Level - see definition in Section 2
S I	Le Système International d'unités (International System of units); modern form of the metric system; the world's most widely used system of measurement; it comprises a coherent system of units of measurement built around seven base units, a number of coherent derived units, and a set of prefixes that act as decimal-based multipliers.
signal-to-noise ratio	the relative amplitude of the acoustic signal from the source compared with background noise; often expressed in decibels (dB)
source	An object that radiates sound, either intentionally (eg an echosounder) or unintentionally (eg a ship's propeller)
Source Level (SL)	a measure of the acoustic output of a source which is independent of the environment; may be related to sound energy or power output; Source Level is sometimes stated as a spectral level as a function of frequency (eg in third-octave bands) or as a broadband level (summed over all the frequencies of radiation); Unit: dB re 1µPa referred back to 1 m; see definition in Section 6
soundscape	a qualitative way of describing the noise field in terms of frequency content, temporal and spatial variations, and types of source
spectrum	a quantity expressed as a function of frequency, either as a narrowband spectrum (eg 1 Hz bands) or as aggregated bands (eg third-octave bands)
SPL	Sound Pressure Level – see definition in Section 2
Transmission Loss (TL)	synonym for acoustic Propagation Loss; reduction of sound level with range; expressed in decibels
TOB	Third Octave Band, frequency band consisting of one-third of an octave, an octave representing a doubling of frequency

11. Annex B: Examples of appropriate modelling approaches

11.1 Modelling techniques

As pointed out in Section 7, the wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations. However, the propagation of sound in the ocean has been the subject of study for many decades, and it is possible to make accurate estimates of the propagation of sound if sufficient information is available about the environment. A model will make use of information about the water column itself (sound speed profile, absorption, bathymetry), seabed (sound speed, density, absorption), sea surface (roughness, bubble presence) and the depths of source and receiver.

Models are generally categorised as range independent (the input parameters are kept fixed), and range dependent (input parameters such as water depth and sound speed are allowed to vary with range from the source). There are a wide variety of models available, some of which are available to download free of charge, but these complex models require some expertise to run them successfully. The models may be categorised generally into a number of classes [Jensen *et al* 2000, Weston 1976]:

- Ray tracing models
- Normal mode models
- Parabolic equation model
- Wavenumber integration models
- Energy flux models

The methods listed above are described in detail in the books by Jensen *et al* [Jensen *et al* 2000], and Etter [Etter 2013]. The exception is Weston's flux integral method which can be applied to arbitrary seabed bathymetry [Weston 1976] and has recently been extended to include convergence effects for arbitrary sound speed profiles [Harrison 2013].

11.2 Available modelling software

There are a number of examples of appropriate modelling approaches which can be found on open access websites. Some of these web-sites contain acoustic modelling software which is freely-available to download, and which has been benchmarked against measured data (and compared with other models).

One such example is the *Ocean Acoustics Library*, which is supported by the U.S. Office of Naval Research (Ocean Acoustics Program) as a means of publishing software for general use to the international ocean acoustics community. For details, see http://oalib.hlsresearch.com/

Another source of propagation modelling software is provided by the AcTUP graphic user interface which simplifies pre- and post-processing when running some of the software code available from the Ocean Acoustics Library. AcTUP is available from the Centre for Marine Science and Technology of Curtin University, Australia: see http://cmst.curtin.edu.au/products/actoolbox.cfm

Note that the modelling software described above requires some expertise to run, and care is still required when interpreting results. However, once sufficient experience and knowledge have been gained, the above code provides access to benchmarked propagation modelling software.

11.3 Sources of auxiliary and environmental data

There are a number of sources of basic information needed as input parameters for modelling.

Vessel movements

For data on large and many small ship movements, the Automatic Identification Systems (AIS) can be used, since all large merchant vessels are required to carry an AIS-transponder on board. For information, see http://www.marinetraffic.com/ais/

Source level data

Most propagation models require the source output to be described by a monopole source level. For information on source levels of specific sources, see the scientific literature in learned journals. Note that many publications on radiated noise from ships, including the ANSI Standard S12.64-2009 [ANSI, 2009] and ISO PAS 17028 [ISO 2012], do not report the monopole source level, but the radiated noise level (though some still refer to the quantity as "source level"). Some scientific papers refer to an "effective source level" when a simple spreading law such as 15.log(R) has been used to account for propagation loss. As pointed out in Section 6, this does not result in a monopole source level and data so derived should not be used with models which require a monopole source level as an input parameter.

Sound speed profiles

Of particular importance in deep water is the sound speed profile, and data are available in the World Ocean Atlas 2009. See http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html

The NPL website also contains useful information and interactive equations for calculating the speed of sound in sea-water as a function of temperature, salinity and pressure (or depth): http://resource.npl.co.uk/acoustics/techguides/soundseawater/

Bathymetry

Of particular importance in shallow water is the bathymetry. Global bathymetry data may be obtained at the following sites:

http://www.ngdc.noaa.gov/mgg/global/

http://www.gebco.net/

http://gcmd.nasa.gov/records/GCMD_DBDBV.html);

The latter provides sediment composition, often available from geophysical surveys.

Sound absorption

A summary of the absorption of sound in seawater is described on the website of the NPL: see http://resource.npl.co.uk/acoustics/techguides/seaabsorption/

Sediment properties

Data for the acoustic properties of marine sediment for use in models can be found in the papers of Hamilton [Hamilton 1980].

12. Annex C: Summary of guidance notes

Summary: Acoustic Metrics

The most appropriate metrics for use with **pulsed sounds** are:

- Single pulse Sound Exposure Level (SEL)
- Cumulative Sound Exposure Level (SEL) (for a series of pulses);
- Peak sound pressure level;
- Peak-to-peak sound pressure level.

It may also be useful to calculate the peak compressional sound pressure level and peak rarefactional sound pressure level, the pulse duration, and the pulse repetition frequency.

The metric most suitable for **continuous sounds** (including ambient noise) is:

- Sound Pressure Level (SPL).

Note that by convention, this is a time-averaged quantity and is most commonly understood as an RMS value. The averaging time used in the calculation of the values of SPL must be stated.

Where continuous sounds also contain transient or pulsed sounds from specific events, the metrics used for pulsed sounds should be used to describe these specific events.

Summary: Measuring Instrumentation

Ensure measuring system performance is fit for purpose. Key performance parameters include:

- Sensitivity (3.1.1)
- frequency response (3.1.2)
- directivity (3.1.3)
- system self-noise (3.1.4)
- dynamic range(3.1.5).

The performance of any commercial off-the-shelf systems should be validated (3.1.6).

The measuring system should be calibrated over the full frequency range of interest (3.2.1).
Ensure appropriate quality assurance procedures are applied to the measurement (3.2.2 & 3.2.3).

Data storage should ideally be lossless format and include all necessary metadata and calibration information (3.3).

Summary: Deployments

Ensure deployment configuration is appropriate for measurement requirements with hydrophones deployed at appropriate depths (4.1 & 4.2).

Ensure deployment related parasitic signals are minimised, including those originating from:

- Flow noise (4.3.1)
- Cable strum (4.3.2)
- Surface heave (4.3.3)
- Vessel/platform noise (4.3.4)
- Mechanical noise (4.3.5)
- Electrical noise (4.3.6)

Record all auxiliary data and metadata (4.4).

Ensure steps are taken to protect recorders and data from loss (4.5).

Summary: Ambient noise measurement

Ensure that the objectives of the measurements are clear and that the monitoring and deployment configuration is appropriate for those objectives (5.1 & 5.3).

Ensure that the temporal sampling regime is appropriate for the objectives, and that the duration and duty cycle are appropriately chosen (5.3).

Ensure that the spatial sampling regime is appropriate for the objectives, and that the locations of monitoring stations are appropriately chosen (5.3).

Ensure that the instrumentation is correctly specified for the application (for example, in terms of frequency range, dynamic range and self-noise) (5.3.2).

Ensure the deployment minimises measurement artefacts and parasitic signals (5.3.3).

Document and justify choice of data analysis methodology in terms of:

- Metrics – arithmetic mean and median are recommended (5.4.3);
- Averaging procedure – choice of snapshot time (5.4.4);
- Statistical representation of data – representing dispersion of data by use of analysis such as box-plots, and cumulative distributions (5.4.5).

Record all relevant auxiliary data and metadata including data which may correlate with acoustic data (ship traffic data, weather data, etc) (5.3.3).

Summary: Radiated noise measurement

Ensure that the objectives of the measurements are clear and that the measurement configuration is appropriate for those objectives (6.1 & 6.2).

Ensure that the source output metrics are appropriate for the objectives, and that the measurement configuration enables the chosen metrics to be derived (6.2).

If a source level is calculated, ensure that an appropriate propagation model is used which accounts for the relevant physical propagation phenomena (6.2.3).

Ensure that the measurements satisfy the requirements of the objectives such that:

- the instrumentation is correctly specified for the application in terms of frequency range, dynamic range and self-noise (6.3.6, 6.3.7);
- spatial sampling is appropriate to ensure far-field conditions (6.1.4) and (if required) to provide an empirical check on propagation (6.3.2);
- the temporal sampling captures any variation in acoustic output using a fixed (static) recording position (6.3.1);
- the deployment minimises measurement artefacts and parasitic signals (6.3.7);

contaminating noise sources are minimised (or eliminated) (6.3.8).

Summary: Propagation modelling

Ensure that the choice of model is appropriate for the application (7.3).

Ensure that the propagation model used accounts for the physical propagation phenomena relevant to the scenario, including the following potential influencing factors (7.4):

- range-dependent bathymetry including dependence on varying water depth and the frequency cut-off for the channel;
- sound speed including the sound speed profile (especially for deeper water);
- frequency dependence, including absorption in the water;
- seabed properties, including propagation within the seabed;
- interaction with the sea surface, including the effect of surface roughness.

Preferably, use a model that has been benchmarked against historical experimental data or by comparison with other propagation models, or check consistency with range-dependent measured data from current experimental work (for example, when measuring radiated noise).

Summary: Uncertainties

All measurements require an estimate of uncertainty in order to be useful.

Uncertainties may be categorised into two classes (8.1):

- Type A: a measure of the repeatability of the measurement (derived from the statistical dispersion of repeated measurements);
- Type B: a measure of uncertainty due to any the systematic bias.

There are a number of potential sources of uncertainty (8.2):

- calibration of instrumentation;
- position of source and receiver;
- spurious signals introduced by the deployment
- validity of any assumptions made;
- environmental parameters (for use in a propagation model).

Uncertainties may be evaluated by following the international Guide to the Expression of Uncertainty in Measurement (8.3)

Measurement uncertainties are an attempt to quantify how accurately we are able to measure a quantity, and should not be confused with natural fluctuations and variability in a quantity (for example, the potentially large variations in ambient noise due to changes in weather, etc).