Best Practice Guide for Underwater Particle Motion Measurement for Biological Applications

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List of Abbreviations

ADC	analogue to digital converter
ADEON	Atlantic Deepwater Ecosystem Observatory Network
ANSI	American National Standards Institute
BIPM	International Bureau of Weights and Measures
CSA	CSA Ocean Sciences Inc.
CTD	conductivity temperature depth probe
DC	direct current
DFT	discrete Fourier transform
EPWI	equivalent plane wave intensity
ESD	energy spectral density
ESDL	energy spectral density level
Exeter	University of Exeter
FOI	Swedish Defence Research Agency
GPS	Global Positioning System
GUI	graphical user interface
Hz	hertz
IEC	International Electrotechnical Commission
IEPE	Integrated Electronic Piezo-Electric
IOGP	International Association of Oil & Gas Producers
ISO	International Organization for Standardization
ISQ	International System of Quantities
JASCO	JASCO Applied Sciences
JIP	E&P Sound and Marine Life Joint Industry Programme
JOMOPANS	Joint Monitoring Programme for Ambient Noise North Sea
MATLAB™	Matrix Laboratory (software)
MEMS	microelectromechanical system
NA	not applicable
NPL	National Physical Laboratory
PAEL	sound particle acceleration exposure level
PAELx	sound particle x-acceleration exposure level
PAL	mean-square sound particle acceleration level
PALx	mean-square sound particle x-acceleration level
PDEL	sound particle displacement exposure level
PDELx	sound particle x-displacement exposure level
PDL	mean-square sound particle displacement level
PM	particle motion
PSD	power spectral density
PSDL	power spectral density level
PVC	polyvinyl chloride
PVEL	sound particle velocity exposure level

PVELx	sound particle x-velocity exposure level
PVL	mean-square sound particle velocity level
PVLx	mean-square sound particle x-velocity level
PZT	lead zirconate titanate
rms	root-mean-square
SD	Secure Digital
SEL	sound pressure exposure level
SI	International System of Units
SIL	sound intensity level
SNR	signal-to-noise ratio
SNLD	signal-to-noise level difference
SPL	mean-square sound pressure level
SSP	sound speed probe
TNO	Netherlands Organisation for Applied Scientific Research
UNH	University of New Hampshire
UTC	Coordinated Universal Time
WAV	Waveform Audio File Format
WD	working draft

The problem

All sound comprises fluctuations in pressure and particle motion (PM) and all fishes and many aquatic invertebrates detect PM. Noise is unwanted or harmful sound, and underwater anthropogenic noise is a global pollutant. Therefore, a large proportion of marine life is potentially threatened by PM created by anthropogenic activity. There is building evidence that anthropogenic noise is detrimental to the health and survival of fishes and aquatic invertebrates, but the importance of PM to these effects remains unclear because until recently very few PM measurements have been taken, with studies mainly relying on sound pressure measurements to estimate PM exposure levels. In theory, PM cannot be predicted effectively from sound pressure in certain physical conditions. These physical conditions tend to be near the surface and the bottom, or in shallow water such as near shore, in lakes and rivers etc., where most aquatic life is found. Thus, there is a need to measure PM to establish the levels at which aquatic life can detect sound, levels at which adverse effects from anthropogenic activity occur, and to establish the boundaries for the physical conditions where sound pressure can or cannot be used to predict PM. PM sensors are becoming commercially available, while some scientists are also making their own, leading to an increase in the number of scientists taking PM measurements around the world. There is a need for guidance that helps scientists to understand what PM is and when it needs to be measured, how to select and calibrate instruments for such measurements, how to properly take measurements and then how to process and report the data for consistency and comparability between studies.

Our solution

Our solution is this 'Best Practice Guide', with the following providing an outline of our key findings on best practice for PM measurement for biological applications. A frequently posed question is: 'Do I need to measure PM?' In order to fully answer this, the expertise of a biologist is required to determine whether PM is biologically relevant, and the expertise of an acoustician is required to determine whether PM could be calculated from pressure measurements. This best practice guide introduces the biological applications of PM measurements in Chapter 1, the scope of the guide in Chapter 2 and some of the basic physical principles of PM in relation to sound pressure in Chapter 3. It is the recommendation of the authors of this guide that PM is of biological relevance if it can be heard (e.g., by the accelerometer-like ears of fishes), if it risks causing injury, or if sound source direction is of interest to a biological study.

It is also our recommendation that the magnitude (though not necessarily the direction) of PM can be calculated in situations where a plane wave or spherical spreading from a monopole source are reasonable approximations, but in other situations PM should be measured. Factors that could affect plane wave conditions depend on source type, frequency and distance from reflective boundaries. Essentially, in shallow water conditions in open water and in tanks, both sound pressure and PM need to be measured to describe the complete sound field. The physics justifying 'how shallow is shallow?' is explained in Chapter 4 of this guide. The maths describing these relationships has been programmed into a simple calculator where the user can enter physical properties of the acoustic environment and the sound of interest and receive a recommendation about whether PM should be measured or not. This calculator is attached to this guide as supporting material.

Reporting only the pressure component risks underestimating impacts due to PM, particularly close to the source where PM is higher. However, we always recommend reporting sound pressure alongside PM to contextualise PM measurements. Measuring sound pressure gradients can also be an effective way to measure PM. In Chapter 5, basic guidance is provided on how to measure sound pressure, including the specifications of system components that can be used and how to deploy them. Measurement systems consist of hydrophone(s), conditioning preamplifier(s), analogue-to-digital converter(s) and a computer. The measuring system may consist of individual components or as an integrated system such as an autonomous recorder. Making effective measurements requires selecting hydrophones with a sensitivity that is well matched to the signals of interest and that the entire system is calibrated over the frequency range of interest.

Sound propagation in and on the seabed can influence sound propagation in the water column. Therefore, a brief overview of behaviour of sound in the seabed is provided in Chapter 6. Interface waves and shear waves can affect the soundscape and these can be measured using geophones coupled to the seabed.

Once the need for measuring PM is established, selecting equipment with which to make measurements is critical. We cover instrumentation in Chapter 7. PM sensors are most commonly based on accelerometers but can also be based on geophones or hydrophone arrays. The entire PM sensor must be calibrated for measurements to be meaningful, and this is covered in Chapter 8. Water salinity, PM sensor waterproofing and suspension methods all influence an instrument's calibration. For best practice, report the calibration in SI units and include the phase response and percentage uncertainty.

Instructions for how to deploy PM sensors to make measurements in open water and in tanks are given in Chapter 9, with checklists to guide the reader. Due to the diversity of instruments and possible suspension types, this guidance is relatively general.

PM recordings are acoustic data that are often stored as 'wav' files, with the main difference from pressure recordings being that PM data involve multiple channels; one for each axis of motion. Therefore, once calibrated, much of the data processing steps are the same for PM data as for sound pressure data. Chapter 10 includes a schematic representation of common analysis pathways and signposts the reader to detailed guidelines on signal processing that are already published. Intensity and integrating data from the three axes to calculate the PM magnitude are covered as well.

Reporting PM is a key area to standardise at this early stage of the field, to ensure comparability between studies, which is the topic of Chapter 11. It is considered essential to report acceleration, with the option to report other quantities such as velocity or displacement if they are relevant to the study. We recommend reporting both linear and logarithmic quantities (i.e., linear and levels) and comparisons between PM and pressure should be like-for-like in terms linear or logarithmic units. For reporting levels in decibels, we provide a table of recommended reference values and recommend reporting the reference value with the quantity rather than the unit to avoid confusion. Finally, in Chapter 12 the key requirements and recommendations of this guide are summarised for making successful measurements. The science of this field is at an early stage and for this reason it is necessary for someone in the measurement team to understand the technicalities well, thus the summary cannot be taken as a short cut.

Why now?

There is an increased public and industrial awareness of PM and a concern that PM from anthropogenic activities can adversely affect aquatic life. These concerns create a need for scientific research involving PM measurements, and increase the likelihood that Environmental Impact Assessments will be required to address PM in the future. There is currently no agreed standard for measuring PM, but scientists need to be able to produce universally comparable data. Our best practice guide is well timed as the field of PM bioacoustics is set to blossom. The current number of scientists making PM measurements is relatively small, thus a significant proportion of the community could attend a workshop that would allow for constructive discussions that will guide the field as it develops.

The inclusive process of writing this best practice guide

Following an in-depth literature review, an interim best practice guide was initially written by the authors. The authors of this guide comprise a multidisciplinary team that have a range of expertise spanning fish biology, the physics of underwater sound, practical experience of making underwater PM recordings, and analysing and reporting the resulting data. The interim best practice guide was rigorously reviewed by a panel of scientists active in this research field, the funder, and several global leaders in this field; and selected independent expert scientists active in the research area of measuring PM. The draft guidance was discussed by this group of selected scientists, the scientific panel, and all the authors at a webinar held in September 2020. At the webinar, directed discussions occurred on topics for which the authors could not agree a best practice. Polls by the webinar contingency followed each topic, which provided guidance for the authors to arrive at consensus on all topics. These agreements are incorporated into this guide. Our intention is to test this best practice guide in a field trial before producing a final version that will serve as a standard for research and industry. The development of this guidance document was sponsored by the E&P Sound and Marine Life Joint Industry Programme (JIP). Other documents the reader may wish to consult include a self-consistent set of procedures developed for use in JIP-sponsored projects (Ainslie et al., 2017; de Jong et al., 2020), and other self-consistent sets developed by the soundscape monitoring projects Atlantic Deepwater Ecosystem Observatory Network (ADEON; e.g., Ainslie et al., 2020a; Heaney et al., 2020) and Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS, e.g., Wang and Robinson, 2020).

1 Introduction

Underwater soundscapes are important for aquatic animals; because other cues attenuate rapidly, sound is a key sensory channel underwater. All sound involves pressure and particle motion (PM) fluctuations (Figure 1). The detection of sound pressure by aquatic mammals and some fishes is well established (Erbe et al., 2016; Houser et al., 2017; Southall et al., 2019), while all fishes and many invertebrates are known to detect PM (Popper and Hawkins, 2018). However, anthropogenic noise pollution threatens natural soundscapes and their inhabitants (Duarte et al., 2021). There is currently no agreed standard for measuring PM, but there is a need to understand the natural and anthropogenic PM present in aquatic environments so that we can assess the risks of human activities to aquatic animals. Further, the PM field needs to be quantified for all studies that investigate fish and invertebrate sensitivity to acoustic cues (Duncan et al., 2016; Nedelec et al., 2016; Rogers et al., 2016). Studies of acoustic ecology can also benefit from understanding PM, particularly when considering the directional information available. There is an awareness of this importance in the scientific community, but standards for how to measure PM are lacking (Halvorsen and Ainslie, 2018; Popper and Hawkins, 2018). A growing number of research groups around the globe are measuring PM in tanks and open water (e.g., Martin et al., 2016; Nedelec et al., 2016; Campbell et al., 2019). To ensure PM measurements are meaningful and comparable between studies, guidelines are required on the calibration of sensors, data collection, and presentation of data with biological relevance. This best practice guide addresses this need.

1.1 Underwater soundscape

The underwater pressure and PM soundscape is a mixture of ‘geophony’, ‘biophony’ and ‘anthrophony’. Geophony is made up of geophysical sound sources such as wind, waves, rain, and lightning. Biophony is composed of biological sounds such as scrapes, snaps and songs made intentionally or unintentionally by animals. Together, geophony and biophony and the ‘acoustic daylight’ they create comprise a natural soundscape that animals have adapted to use in order to survive and reproduce (Buckingham et al., 1996; Pijanowski et al., 2011). Anthrophony is made up of the sounds emitted by human activities such as from powered engines, resource extraction and ocean exploration (Pijanowski et al., 2011). These activities introduce noise, threatening animals’ health and their ability to use the natural soundscape (Duarte et al., 2021). Studies that improve our understanding of the impacts of noise on aquatic life are needed, to strike a balance that mitigates the impacts of noise and permits sustainable anthropogenic activity.

1.2 Sound pressure and particle motion

Sound energy is a disturbance in an elastic medium (water, air, or solid) (ISO 18405:2017 of the International Organization for Standardization (ISO)). Particles of the medium oscillate around a point of origin (called PM) causing local compressions and expansions (called sound pressure) that transfer the sound energy to neighbouring particles (Gray et al., 2016, DOSITS). The frequency of these oscillations is measured in cycles per second, or hertz (Hz) and the sound energy propagates at a speed (m s^{-1}) related to the properties of the medium. The sound PM can be described by particle displacement (m), particle velocity (m s^{-1}), particle acceleration (m s^{-2}), or any higher derivative (ISO 18405:2017). Note that particle velocity (speed of oscillations around a point) is not to be confused with sound propagation speed (speed the sound energy travels from one particle to the next). The sound pressure is described by the fluctuations around the hydrostatic pressure as force per unit area in Pascals (Pa) (ISO 18405:2017).

1.3 When particle motion is of biological importance

PM and the relationship between PM and sound pressure are important to fishes and aquatic invertebrates because of their use of soundscapes and the risk of injury from loud sounds. Measuring and reporting only the pressure is not sufficient to describe the risk of impacts to aquatic animals from anthropogenic noise. Loud impulsive sound pressure waves can rupture gas filled chambers such as swim bladders, causing tissue injuries (e.g., Halvorsen et al., 2012). Impacts on tissues from large PM fluctuations have not yet been examined in aquatic animals and further investigation is needed. Research into strain-related neuron damage suggests that particle displacement may be the causal factor in non-barotrauma tissue damage (Bradshaw et al., 2001). Neurons, like all elastic materials, can only stretch so far before they break. It is not yet known which, if any, PM component (displacement, velocity, or acceleration) may be best correlated with injury in aquatic animals. Note that animals that do not hear sound can still be injured or killed by loud sounds (e.g., plankton mortality during seismic surveys McCauley et al 2017). When investigating physical injuries from anthropogenic sounds, reporting particle motion *and* pressure is therefore necessary.

All fish and many invertebrates detect the PM of a sound wave with mechanosensory organs such as the inner ear, statocyst or lateral line (Webb et al., 2008; McCauley et al., 2017; Popper and Hawkins, 2018). Teleost fish species with a swim bladder may detect sound pressure (Putland et al., 2019; Popper and Fay, 2011). The inner ear, statocyst and the canal neuromasts of the lateral line act as accelerometers, while the superficial neuromasts of the lateral line are sensitive to particle velocity (Budelmann, 1989; Bleckmann, 2004; Mogdans, 2019). It is necessary to measure and report PM magnitude to understand the impacts of anthropogenic noise on masking, stress physiology, cognition, behaviour and, ultimately, fitness.

Aquatic animals have the ability to determine the direction and the distance to a sound source, a key to survival (Bleckmann, 2004; Fay, 2005; Zeddies et al., 2010; Sisneros and Rogers, 2016). In theory, the product of particle acceleration and pressure (i.e., the intensity) allows fishes with pressure detecting abilities to determine sound source direction (Sisneros and Rogers, 2016). Animals that do not have sensitivity to pressure can determine direction through the hair cell orientation patterns, neuronal innervation, and directional movements of the otoliths (Dijkgraaf, 1963), although there are knowledge gaps in how exactly this is achieved. When sound source localisation in pressure-sensitive fishes is of interest or is threatened by anthropogenic noise, reporting sound intensity as a vector quantity (showing the directional component), or PM direction, can therefore help us to understand acoustic ecology from the perspective of aquatic animals. Additionally, the direction of sound travel is not available from single hydrophone recordings, however intensity or PM direction can enable tracking of animals, studies of their distribution, and investigations of interactions between aquatic life and human sound sources. Furthermore, when waves are propagating within the seabed or along the seabed-water interface, the seabed acts as a sound source. Therefore, near-field effects can be observed in the water column close to the seabed boundary in the evanescent field. See Section 6.3 for details of waves that may occur within the seabed and at the seabed-water interface. See Appendix A for the definitions of terms including level, amplitude and intensity, as there are important distinctions between these terms.

1.4 Importance of interdisciplinary collaboration

Our overarching recommendation is to establish a multidisciplinary team with the necessary expertise in the specific biological field(s), the physics of underwater sound, the PM sensor function, and knowledge of programming and digital data processing. Scientists trained in different disciplines use and comprehend different languages, terminology, and communication styles, which can lead to communication challenges. Such a team will function effectively with the adoption of agreed terminology and reporting conventions. The team of authors developing this best practice guide have tried to lead by example. The diverse expertise required means that one individual may not necessarily comprehend the entirety of this best practice guide, however, expertise in each of the areas covered by this guide is needed within the research team.

1.5 Best practice

Best practice is defined as a series of guidelines, ideas and rationale that represent the most effective and/or judicious course of action. The guidance in this document was established as follows. An interim best practice guide was initially written by the authors. The interim best practice guide was rigorously reviewed by a panel of scientists active in this research field, the funder, and a range of selected independent expert scientists from across the globe active in the research area of measuring PM. The draft guidance was discussed by this group of selected scientists, the scientific panel, and all the authors at a webinar held in September 2020. At the webinar, directed discussions occurred on topics for which the authors could not agree a best practice. Votes by the webinar contingency followed each topic, which provided guidance for the authors to arrive at consensus on all topics. The agreements reached by consensus are incorporated into this guide. Our intention is to test this best practice guide in a field trial and refine the guidance herein. The result will ultimately serve as a standard for research and industry.

1.6 Requirements and recommendations

Our requirements and recommendations for successful measurement of PM are provided at the end of each chapter within a shaded box. Requirements are necessary to avoid errors and are indicated using the word ‘shall’ throughout the text, while recommendations reflect the authors’ consensus on best practice and are indicated using the word ‘should’.

1.7 Terminology

Use of clear and unambiguous terms and definitions is an essential pre-requisite for effective inter- and intra-disciplinary communication (Figure 1). Acoustical terminology in this Best Practice Guide follows ISO 18405 and the JIP terminology standard (Ainslie et al., 2018a). Additional terms and definitions used in this report are provided in Appendix A.

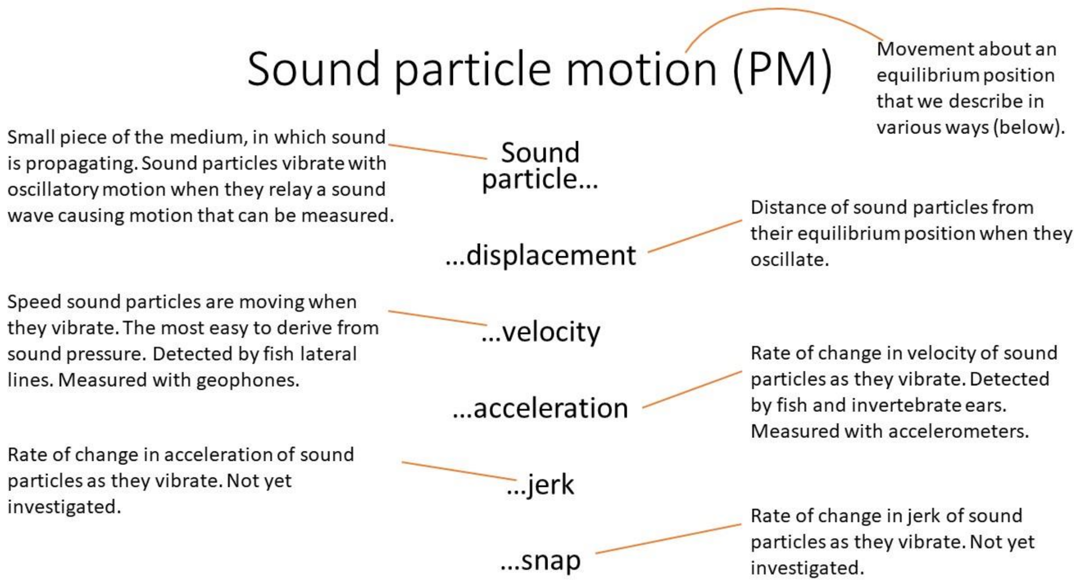


Figure 1 Terminology of particle motion. In this guide the word particle refers to sound particles. Note that sound particles are pieces of the medium in which the sound propagates and not a type of particle specific to sound (as a photon is for light).

2 Scope

This Best Practice Guide is aimed at scientists who wish to measure or understand measurements of underwater PM for biological applications. Use of the guide is not intended to (and does not) pre-empt the need to engage with experts in both biological and physical aspects of bioacoustics. The multidisciplinary nature of the detailed information in this guide means that not every individual will be able to read and understand the entire document. However, expertise in each of the multidisciplinary aspects contained in this document is needed within the team of scientists who will plan, make, and analyse these measurements. The purpose of this guide is to arm the user with knowledge to help select expertise needed for the team and engage in discussions with experts. Following the recommendations in this guide will facilitate transferability and reproducibility of study results to other projects and research groups.

The intention is that this best practice guide can be used to:

- establish if PM needs to be measured or can be calculated from sound pressure;
- critically appraise PM sensor specifications and their calibrations;
- plan and execute a scientific investigation to successfully measure PM in the water column;
- ensure that analysis and reporting of PM data is aligned with the best expert knowledge in the field;
- signpost the user to existing relevant guides for best practice (e.g., acoustic signal processing guide JIP terminology standard (Ainslie et al., 2018a) and acoustical terminology (ISO 18405:2017)).

What is this guide?

This is the Best Practice Guide for Particle Motion Measurement for Biological Applications

'Best practice guide' (see section 1.5): This guide contains recommendations and requirements for courses of action that have been, as democratically as possible, decided upon as the most rational. Wherever possible we justify the guidance in this document with explanations of the rationale used to define it as best practice.

'Particle motion measurement': PM in this document refers to acoustic particle motion. Measurement of PM means making acoustic recordings that are calibrated and reported in a way that can be interpreted by others in the field.

'Biological applications' are defined here as anything relevant to animals living in the water column and on the sea floor, but not buried in the sediment.

What is in this guide?

This guide contains practical guidance and explanations of rationale behind choices for best practice on equipment, calibration, making measurements of received levels, data analysis and reporting. The necessary parts of a sensor that measures PM are described. Sound intensity is included because it is a vector quantity that is relevant to sound source localisation, an important aspect of this growing field. Key requirements and recommendations are provided for when to measure PM, calibration, measurement, and data processing, with the goal of improving data quality and comparability between projects. Measurement of sound pressure is discussed because it is needed to calculate intensity and because it can be used to estimate PM. Measurement of sound pressure is always recommended alongside measurement of PM to provide a comparison and gain an understanding of the relationships between pressure and PM, as well as to validate the measurement of PM. Measurements in tanks and open water are discussed because, despite the complex sound fields in tanks, it is recognised that some work in tanks can progress understanding of biological organisms in the wild. Some of the concepts of seabed vibrations are included because of their relevance to measurements of PM in the water column, but there are no details provided for how to measure seabed vibrations nor how to calibrate geophones. The focus is on instrumentation, calibration, measurement practices, and terminology for recording sound PM with accelerometers or hydrophone pairs.

Limitations (what is not in the scope)

The scope of this best practice guide is limited to PM from sound waves (not other types of PM such as those associated with water flow). This guide is also limited to measurement of PM in the water column, consideration of PM in the sediment and its effects on animals that inhabit the sediment are important, but their measurement is beyond the scope of this guide. Processing and reporting of directional information are beyond the scope of this guide. Acoustic modelling of soundscapes in terms of sound pressure, sound PM, and intensity are beyond the scope of this guide. Source levels are beyond the scope of this guide.

Limitations (what is unknown)

There are several unknowns in the field that are beyond the scope of this guide. These include determining which component is most relevant, particle displacement, velocity, or acceleration for acoustically induced injuries. The PM component that is most biologically relevant will be the subject of future investigation. This is a young field and thus it is expected that knowledge will advance rapidly, this guide serves to assist scientists to make this progress, while also ensuring comparability between different studies.

Why is this guide needed?

There is an urgent need for a PM measurement standard that provides a basis to allow comparability between studies, provide knowledge to scientists to properly employ available sensors, and inform sound exposure criteria regarding PM for fishes and invertebrates. Such standards and recommendations would be highly applicable to environmental impact assessments. Once PM measurement standards are implemented, the scientific basis and understanding of fish and invertebrate hearing, use of sound, and impacts of noise will all improve. To produce this guide, we unified expert scientists from around the globe to share and deliberate. The authors then arrived at consensus upon best practices. This guide is an important first step towards a standard because it provides best practice with scientifically supported rationale.

3 An Introduction to the Physics of Particle Motion

The purpose of this chapter is to introduce readers to some of the concepts, scales, and effects of PM as a background for the rest of the Best Practice Guide. We begin by introducing the relationships between sound pressure and PM, to elucidate why they are closely related to one another, but not always equivalent. We introduce the directional component of PM vectors and intensity, due to the importance and novelty of understanding the directional information available in underwater sound. We then show a direct comparison of displacement, velocity, and acceleration levels with the typical sound pressure levels of ocean background noises at different frequencies (the 'Wenz curves', (Wenz, 1962)), to contextualise the scale of PM in relation to well-known ambient sound pressure levels.

3.1 Concepts

Sound is different from light, in that sound transmits energy by moving the medium it is traveling in back and forth whereas light can move through vacuum. Therefore, the motion of the material elements ("sound particles") that make up the medium (air, water, or solid) is an intrinsic aspect of sound. Measuring PM facilitates the inference of the direction the sound is travelling towards, or equivalently the direction to the sound's source. A succinct introduction to the concepts of PM are provided in Nedelec et al. (2016). Here we provide further relationships that are useful for understanding how to calculate and interpret PM.

Relationship between sound pressure and particle motion

Particle motion magnitude (but not direction) can be approximated from the sound pressure in simplified circumstances such as a plane wave (see Chapter 4). This section uses the wave equation and Euler's equation to explain how we derive the magnitude of particle velocity from sound pressure in a plane wave and why close to the source (in terms of wavelength) of a spherical wave, particle velocity is higher than would be predicted from the sound pressure with the plane wave approximation.

How we derive the magnitude of particle velocity from the sound pressure in a plane wave:

The wave equation is a second-order linear partial differential equation that describes the behaviour of classical waves in space and time. The three-dimensional wave equation considers the spatial dimensions $x, y\ and\ z$ implied by ∇:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p \qquad \text{Equation 1}$$

where

t = time
∇ = gradient operator
c = the speed of the wave
p = sound pressure.

This applies to any sound field. A sinusoidal wave is a solution to the wave equation. Therefore, in acoustics, the wave equation can be used to describe a pure tone propagating as a plane wave. At one point in space:

$$p(x) = A\cos\left(\frac{2\pi}{T}t\right) \quad \text{Equation 2}$$

where

A = sound pressure amplitude (maximum departure from equilibrium pressure)
x = one of three dimensions (x, y, z)
T = period.

In order to describe how this changes with distance as time increases, we subtract a distance dependent phase shift:

$$p(x,t) = A\cos\left(\frac{2\pi}{T}t - \frac{2\pi}{\lambda}x\right) \quad \text{Equation 3}$$

where λ = one wavelength.

This means the wave will reset after one wavelength in space and one period in time. i.e., when $x = \lambda$ and $t = T$ the space and time terms become 2π, and cos(0) = cos(2π). The spatial term $2\pi/\lambda$ is known as the wavenumber, represented by 'k' using the unit radian per metre (rad/m). The temporal term $2\pi/T$ is known as the angular frequency, represented by 'ω' using the unit radian per second (rad/s). Thus, a solution for the acoustic wave equation at a single frequency is often written as:

$$p(x,t) = A\cos(\omega t - kx) \quad \text{Equation 4}$$

Side notes about frequency in Hz. To understand how this relates to temporal frequency (f in Hz) we note that $1/T = f$ and $\lambda = c/f$ (where c = speed of sound and f = frequency), if we want to describe the wave using temporal frequency rather than angular frequency (as reporting is usually in Hz rather than rad/s), we can write this as:

$$p(x,t) = A\cos\left(2\pi f t - \frac{2\pi f}{c}x\right) \quad \text{Equation 5}$$

Now that we have described the wave equation, we can use it in combination with Euler's equation to explore the relationship between sound pressure and particle motion. Here we consider part of the derivation of the acoustic wave equation that is based on Newton's second law relating the force $\boldsymbol{F}$ on an object of mass m and the resulting acceleration, $\boldsymbol{F} = m\boldsymbol{a}$. Specifically using Euler's equation, we can relate the force per unit area (pressure) to acceleration as:

$$\boldsymbol{a} = \frac{-\boldsymbol{\nabla} p}{\rho} \quad \text{Equation 6}$$

where

ρ = mean density of the water
p = sound pressure
∇ = spatial gradient operator
$\boldsymbol{a}$ = acceleration of the water particle (Pierce and Beyer, 1990).

Side notes about direction. The spatial gradient operator for sound pressure is calculated as the pressure difference between two points in space divided by the distance between those points. The two points describe the axis along which acceleration can be calculated via Equation 6. Finding the differences along three orthogonal axes (x, y, z) yields a vector that describes the axis of sound propagation, revealing the direction of the sound source with 180° ambiguity. Velocity is the time integral of acceleration, while displacement (or distance), is the time integral of velocity. In the opposite order, velocity is the time-rate-of-change (or time derivative) of displacement, and acceleration is the time-rate-of-change of velocity. The 180° ambiguity can be resolved via the intensity (see below).

By applying the gradient operator (differentiating the right-hand side of Equation 4 with respect to x) we obtain the acceleration as:

$$a(x,t) = -\frac{A\omega}{\rho c}\sin(\omega t - kx).$$ Equation 7

We can then obtain the velocity (u) by integrating the acceleration over time:

$$u(x,t) = \frac{A}{\rho c}\cos(\omega t - kx)$$ Equation 8

Comparing the equation for u with the equation for p, we can see that to describe the u in terms of p the amplitude and $\cos(\omega t - kx)$ terms will cancel, leaving a simple equation for describing the relationship between the magnitude (but not the direction) of the particle velocity and sound pressure for a plane wave:

$$u = \frac{p}{\rho c}$$ Equation 9

Close to the source of a spherical wave relative to wavelength, particle velocity is higher than would be predicted from the sound pressure with the plane wave approximation.

A spherical wave has a spatial origin at radial distance r = 0 and continues for all time (t). If we know the amplitude of the sound at the source (the source factor, Ainslie, 2010) and we want to predict the sound pressure amplitude at r we can describe a wave that decreases in amplitude with distance from the source by replacing the amplitude term with a factor that decreases with r:

$$p(r,t) = \frac{\sqrt{2S}}{r}\cos(\omega t - kr)$$ Equation 10

where S is the source factor (Ainslie, 2010).

By applying the gradient operator in Euler's equation (differentiating the right-hand side of Equation 10 with respect to r) we obtain the acceleration as:

$$\boldsymbol{a}\,(r,t) = -\omega\frac{\sqrt{2S}}{r\rho c}\left(\sin(\omega t - kr) + \frac{\cos(\omega t - kr)}{kr}\right)\hat{\boldsymbol{r}}$$ Equation 11

where $\hat{\boldsymbol{r}}$ is the unit vector in the radial direction.

By integrating this over time we can show that the velocity is:

$$\boldsymbol{u}(r,t) = \frac{\sqrt{2S}}{r\rho c}\left(\cos(\omega t - kr) - \frac{\sin(\omega t - kr)}{kr}\right)\hat{\boldsymbol{r}} \quad \text{Equation 12}$$

The right-hand side of Equation 12 has two additive terms: the first is the sound pressure term (Equation 10) divided by ρc (the characteristic impedance), the second term is additional and decreases by $1/(kr)$ compared to the sound pressure term. The second term is not present in the pressure field and means that at low frequencies and short ranges from the sound source, the particle velocity is greater than $p/\rho c$, so there is higher amplitude of particle motion compared to what might be inferred from the sound pressure alone. The amplitude $u(r,t)$ (a scalar quantity) is given by

$$u(r,t) = \frac{\sqrt{2S}}{r\rho c}\left(1 + \frac{1}{(kr)^2}\right)^{1/2} \quad \text{Equation 13}$$

For large distances or high frequencies, the relationship between sound particle velocity and sound pressure simplifies such that the second term in Equation 12 may be neglected (kr >> 1, or wavelengths << r):

$$\boldsymbol{u}(r,t) = \frac{\sqrt{2S}}{r\rho c}\left(\cos(\omega t - kr)\right)\hat{\boldsymbol{r}} \quad \text{Equation 14}$$

Comparing the equation for velocity in a spherical wave with the equation for the sound pressure in a spherical wave we can see that when the second term in Equation 12 is negligible (kr >> 1, or wavelengths << r), the relationship between the velocity and the sound pressure is the same as for a plane wave:

$$u = \frac{p}{\rho c} \quad \text{Equation 15}$$

Since sound pressure is a scalar quantity, the value of u is the absolute value = $\sqrt{{u_x}^2 + {u_y}^2 + {u_z}^2}$. When the second term in Equation 12 is negligible, it is then straightforward to find the acceleration and displacement by taking the derivative or integral of the velocity and divide by ρc. Disregarding changes in phase, the acceleration is the time derivative of the velocity which is $2\pi f$ times the velocity while the displacement is the integral of velocity which is simply $u/(2\pi f)$.

Intensity

Acoustic energy radiated away from a source is expressed by the sound intensity (*I*) (ISO, 2017, see also section 10.3):

$$\boldsymbol{I}(r,t) = p(r,t)\,\boldsymbol{u}(r,t). \quad \text{Equation 16}$$

Substituting for p and $\boldsymbol{u}$ in Equation 16 we find

$$\boldsymbol{I}(r,t) = \frac{2S}{r}\cos(\omega t - kr)\left(\frac{\cos(\omega t - kr)}{r\rho c} - \frac{\sin(\omega t - kr)}{r^2\rho ck}\right)\hat{\boldsymbol{r}}, \qquad \text{Equation 17}$$

the time-averaged value of which is

$$\overline{\boldsymbol{I}(r,t)} = 2S\frac{1}{r}\overline{\cos^2(\omega t - kr)}\left(\frac{1}{r\rho c}\right)\hat{\boldsymbol{r}}. \qquad \text{Equation 18}$$

The average value of the cosine squared function is one half, so this simplifies to

$$\overline{\boldsymbol{I}(r,t)} = \frac{S}{\rho c r^2}\,\hat{\boldsymbol{r}}, \qquad \text{Equation 19}$$

From Equation 10 and Equation 12, the root-mean-square (rms) sound pressure and sound particle velocity are

$$p_{\mathrm{rms}}(r) = \frac{S^{1/2}}{r} \qquad \text{Equation 20}$$

and

$$u_{\mathrm{rms}}(r) = \frac{S^{1/2}}{r\rho c}\left(1 + \frac{1}{k^2r^2}\right)^{1/2}. \qquad \text{Equation 21}$$

The rms particle velocity includes a term ($k^{-2}r^{-2}$, in parentheses) that does not contribute to the time-averaged sound intensity. Meaning, the particle velocity close to the source exceeds $p_{\mathrm{rms}}/\rho c$, the value expected from far-field considerations alone, and this near-field discrepancy increases with decreasing frequency and decreasing range. This additional near-field particle velocity contributes to the instantaneous near-field sound intensity (although not the time averaged intensity) and is out of phase with the sound pressure. The additional near-field particle velocity is due to uncompressed flow and does not propagate via elastic compression and rarefaction of the medium and therefore does not contribute to the far-field intensity.

3.2 Computing displacement and acceleration

Particle motion amplitudes can be computed from the sound pressure when Equation 9 is valid. The displacement (δ) is the time integral of velocity, which for sampled data is

$$\delta(t) = \sum_{0}^{t}\frac{p(t)\,\mathrm{d}t}{\rho c} \qquad \text{Equation 22}$$

where dt is the sampling interval, we can simply sum the sound pressure at each time step multiplied by the sampling interval and divided by the characteristic impedance. Numerically this is a stable operation, as long as the average value of $p(t)$ is zero.

Acceleration is the time derivative of velocity, which for sampled data is

$$a(t_n) = \frac{p(t_n) - p(t_{n-1})}{\rho c \, \mathrm{d}t} \qquad \text{Equation 23}$$

Numerically this is more difficult to implement because high frequency noise in the sound pressure can result in erroneous accelerations. This can be mitigated by low-pass filtering or smoothing the data before subtracting $p(t_{n-1})$.

We noted above that when Equation 9 applies, the displacement is the velocity divided by $2\pi f$ and acceleration is velocity multiplied by $2\pi f$. Therefore, if we transform the velocity (or sound pressure by Equation 9) into the frequency domain using a Fourier transform we can compute the acceleration and displacement. The inverse Fourier transform provides time-series of the displacement or acceleration:

$$\delta(t) = \mathrm{Re}\left(\mathrm{IDFT}\left(\mathrm{DFT}(p) \cdot \frac{1}{2\pi \mathrm{i} f \rho c}\right)\right) \qquad \text{Equation 24}$$

$$a(t) = \mathrm{Re}\left(\mathrm{IDFT}\left(\mathrm{DFT}(p) \cdot \frac{2\pi \mathrm{i} f}{\rho c}\right)\right) \qquad \text{Equation 25}$$

where DFT is the discrete Fourier transform of the sampled sound pressure data, IDFT is the inverse discrete Fourier transform and i is the imaginary unit number ($\mathrm{i} = \sqrt{-1}$. The division and multiplication by $2\pi \mathrm{i} f$ in the frequency domain correspond, respectively, to integration and division by time in the time domain. In principle, the result of the forward and inverse Fourier transforms is real (because sound pressure is a real quantity), but small rounding errors lead to small imaginary parts in the output of the IDFT. The purpose of taking the real part is to discard the small imaginary rounding artefact.

3.3 Scales and units

Equation 9 can be used to estimate the scale of particle motions. Consider a continuous sound at 160 Hz with a measured sound pressure of 1 Pa (i.e., 1 kg/(m s^2)) that is far from the source. From Equation 9 the velocity is in the order of 1 µm/s since ρ is ~1025 kg/m^3 and c is ~1500 m/s. The acceleration is $2\pi f u$ which is on the order of 1 mm/s^2 at 160 Hz but would be 1 m/s^2 at 160,000 Hz. The displacement is $u/2\pi f$ which means that for a sound with rms pressure 1 Pa, water 'particles' move back and forth a mere 1 nm at 160 Hz. The displacements get smaller as the frequency increases.

To provide an example of ambient noise acceleration, velocity and displacement, Equation 9, Equation 24 and Equation 25 were used to convert the well-known Wenz curves (Wenz, 1962; NRC, 2003) to their equivalent particle motion curves (Figure 2). The velocity curves have the same shape as the sound pressure curves, while the displacements are amplified at low frequency and reduced at high frequency and the acceleration is reduced at low frequency and amplified at high frequency. In Figure 2, the reference values recommended by ISO 18405 have been used, which has resulted in the acceleration, velocity, and displacement all having the same vertical axes ranges in decibels but with different reference units. The units for the particle motion quantities are summarized in Table 1.

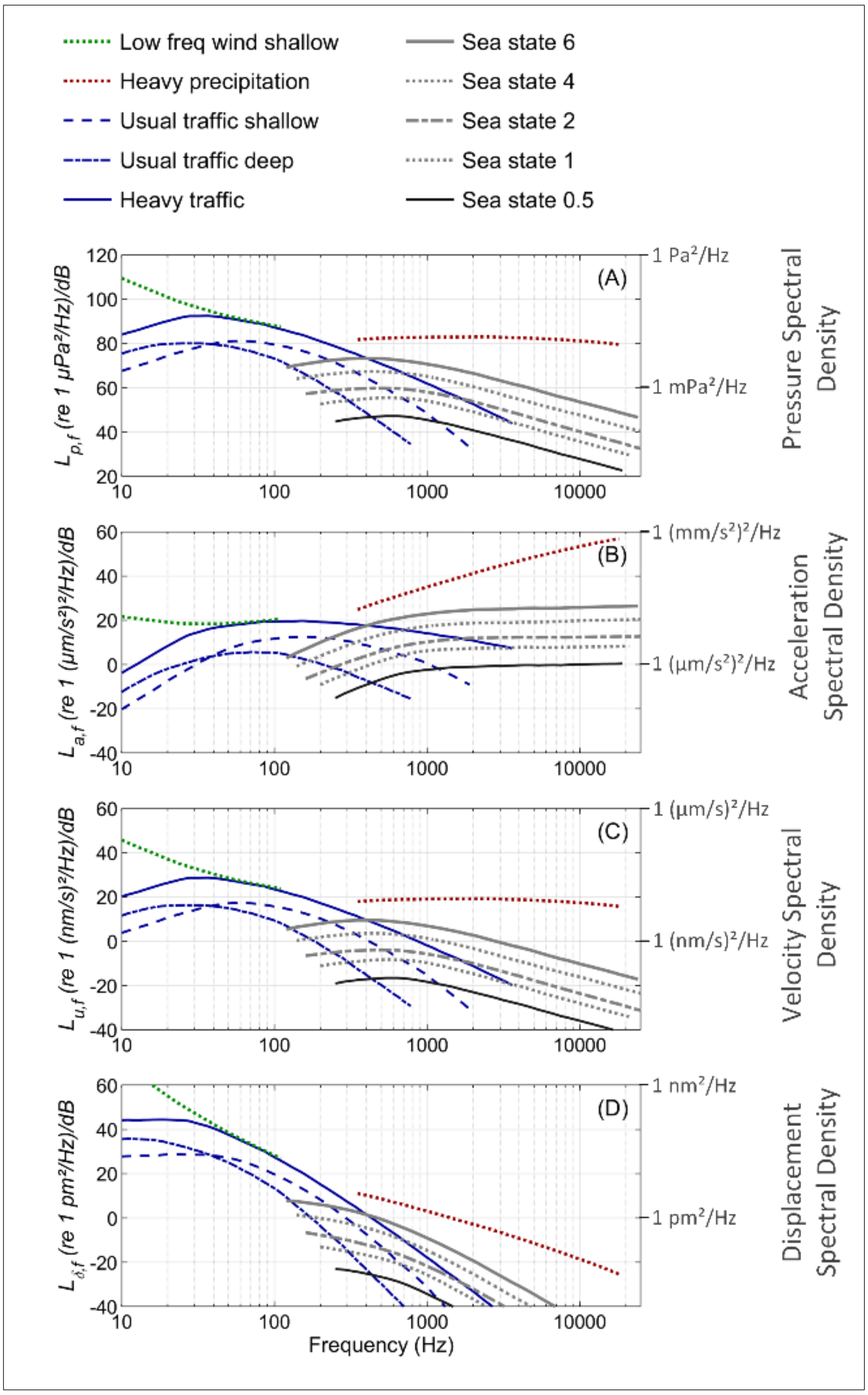


Figure 2 The Wenz curves (Wenz, 1962) scaled to show the range of particle motion spectral densities assuming free-space conditions (Equation 9). (A) – the original Wenz curves as sound pressure spectral density. (B) The Wenz curves converted to velocity spectral density using Equation 9. (C) the Wenz curves converted to displacement using Equation 24. (D) the Wenz curves converted to acceleration spectral density using Equation 25.

Table 1 Summary of recommended units and decibel reference values. The reference value for energy density is a new proposal, consistent with ANSI (1969) of the American National Standards Institute (ANSI). For values for energy spectral density (ESD) and power spectral density (PSD) see Chapter 11 on reporting data.

Quantity	Units	SI Units	Reference for Levels, mainly from ISO 18405 (2017)
Sound pressure, *p*	Pa	$kg/(m\ s^2)$	1 µPa
Sound particle displacement, δ	m	m	1 pm
Sound particle velocity, *u*	m/s	m/s	1 nm/s
Sound particle acceleration, *a*	m/s^2	m/s^2	1 $\mu m/s^2$
Sound intensity, *I*	W/m^2	kg/s^3	1 pW/m^2
energy density, ε	J/m^3	$kg/(m\ s^2)$	1 pJ/m^3

3.4 Energy density

The calculation of energy density facilitates the calculation of energy budgets for diverse source types (Sertlek et al., 2019). It also permits an analysis of the importance of PM in the hydrodynamic near field of an underwater sound source (the region close to a point source within which the velocity is out of phase with the sound pressure, meaning that the PM is higher than would be predicted from the pressure in the far field). The sound pressure contributes potential energy (Kinsler and Frey, 1962)

$$\epsilon_{\mathrm{p}} = \frac{1}{2\rho c^2} {p_{\mathrm{rms}}}^2 \qquad \text{Equation 26}$$

while the particle motion contributes kinetic energy

$$\epsilon_{\mathrm{k}} = \frac{\rho}{2} {u_{\mathrm{rms}}}^2 \qquad \text{Equation 27}$$

where p_{rms} and u_{rms} are the rms sound pressure and particle velocity, respectively. Substituting for these from Equation 20 and Equation 21 gives

$$\epsilon_{\mathrm{p}}(r) = \frac{S}{2\rho c^2 r^2} \qquad \text{Equation 28}$$

and

$$\epsilon_{\mathrm{k}}(r) = \frac{S}{2\rho c^2 r^2}\left(1 + \frac{1}{k^2 r^2}\right) \qquad \text{Equation 29}$$

The total sound energy density is therefore

$$\epsilon_{\mathrm{tot}}(r) = \epsilon_{\mathrm{p}}(r) + \epsilon_{\mathrm{k}}(r) = \frac{S}{\rho c^2 r^2}\left(1 + \frac{1}{2k^2r^2}\right) \qquad \text{Equation 30}$$

or, equivalently

$$\epsilon_{\mathrm{tot}}(r) = \epsilon_{\mathrm{p}}(r) + \epsilon_{\mathrm{k}}(r) = 2\epsilon_{\mathrm{p}}(r)\left(1 + \frac{1}{2k^2r^2}\right) \qquad \text{Equation 31}$$

For a plane wave the average potential and kinetic energies contribute equally to the total. In a spherical wave, the kinetic energy exceeds the potential energy by a factor $1 + (k^2r^2)^{-1}$ from Equation 28 and Equation 29.

The near field is one of the domains where particle motion is of special concern to marine life as the total energy may be 5-10 times greater than the potential energy at low frequencies and at distances of 1-10 m from a relatively small source (Figure 3). In a bounded environment, the kinetic energy may be significant in regions of the sound pressure field where constructive and destructive interference occur, such as near a reflective interface, or where two sound rays might intersect.

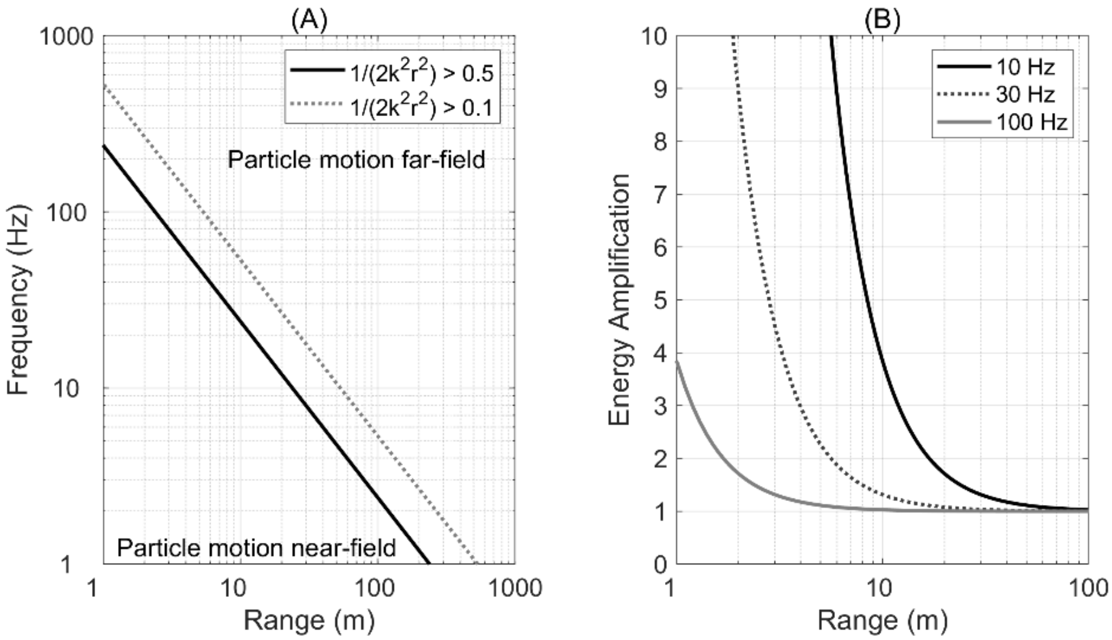


Figure 3 Increase in total energy due to particle motion. (A) Scales of the near-field particle motion effects; the area to the left of the black line is the range and frequency regime where the absolute value of the total energy is more than 2.5 times the potential energy; the dashed grey line defines the area where the total energy falls below 2.1 times the potential energy (the total energy is twice the potential energy in the far field). (B) The amplification of the total energy as a function of range for three frequencies (total energy / 2*potential energy).

4 When to Calculate and When to Measure Particle Motion

PM and intensity should be reported when they are potentially of biological importance (see Section 1.3). Under simplified acoustic conditions, such as when a plane wave or spherical spreading from a monopole source are suitable approximations, calculating PM and intensity from measurements using a single hydrophone is relatively simple. In this section, various conditions that influence calculation of PM from sound pressure measurements are outlined. Recommendations are provided on how to calculate PM and intensity from sound pressure within the physical limitations. A limitation of the PM or intensity calculated from a sound pressure measurement using a single hydrophone is that only the scalar quantities can be determined, which means that directional information is not available. Limitations on the direct measurement of PM are also discussed.

There are three methods for reporting PM:

- Calculating from sound pressure measurements from a single hydrophone;
- Calculating from a pressure gradient measured from a hydrophone array;
- Measuring PM directly with a suitable instrument, e.g., accelerometer or geophone.

There are two methods for reporting intensity:

- Calculating from squared sound pressure (equivalent plane wave intensity or EPWI, not recommended as does not include directional information)
- Calculating from sound pressure and measured PM.

A simplified schematic showing the decision-making process for whether PM and intensity can be calculated from sound pressure or should be measured directly is shown in Figure 4. The physical dependencies for these decisions are explained below.

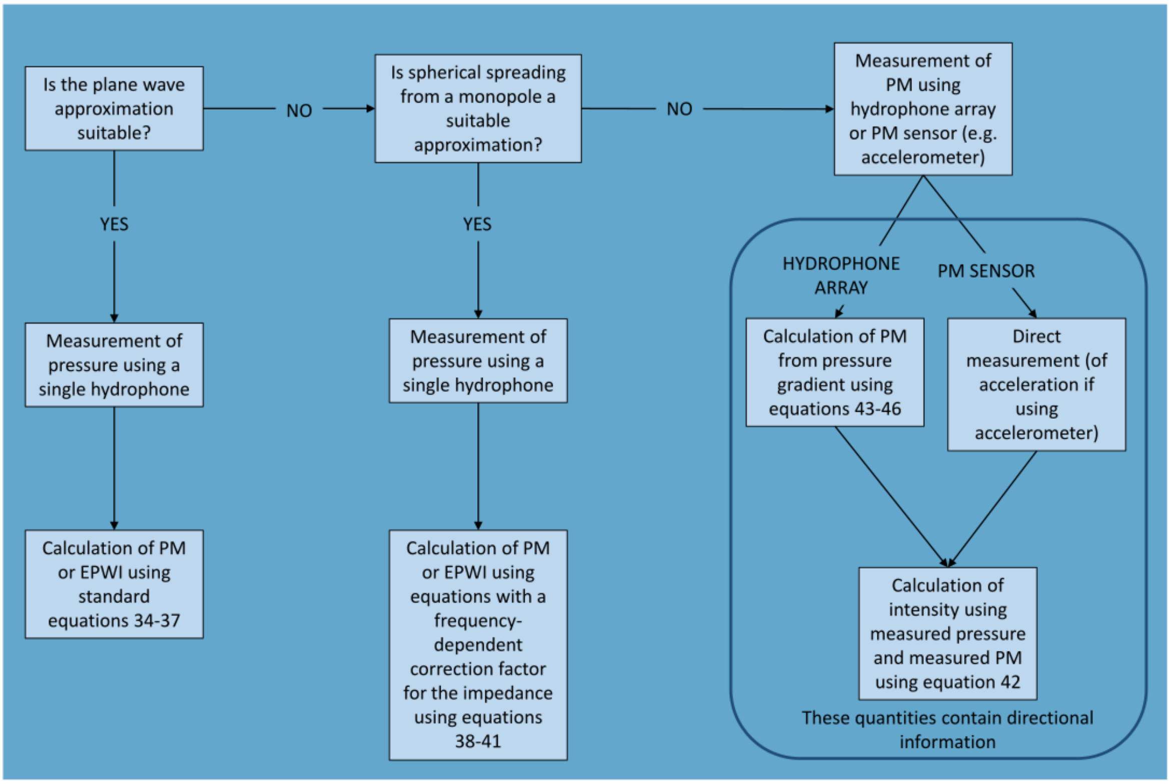


Figure 4 Schematic representation of the decisions involved in when to calculate and when to measure PM directly. When PM is measured directly, then intensity can be calculated using the measured sound pressure and PM.

4.1 When a plane wave or spherical spreading from a monopole are suitable approximations PM and EPWI can be calculated from a single sound pressure measurement

There are times when a plane wave or spherical spreading from a monopole are suitable approximations for PM, which allow for PM magnitude (but not direction) to be calculated from a sound pressure measurement. Spherical spreading occurs when sound is propagating from a source with no interference. A plane wave is a propagating sound wave far enough from its source that the wave front is considered flat and there are no other waves (including reflections) interfering with its propagation. The applicability of the plane wave approximation is dependent on the frequencies of interest and the properties of the 'waveguide' (the water depth, distance to the sound source, source type and the sound speeds in the water and the sediment). A monopole is a point source that radiates equally in all directions. This section provides details that will help users to determine suitable approximations whether it be the plane wave or spherical spreading from a monopole source. If either, the plane wave or spherical spreading from a monopole, approximations are suitable, then PM can be calculated from a single sound pressure measurement. If neither of these approximations are suitable, then PM should be measured using either the pressure gradient method or directly using an appropriate sensor such as an accelerometer.

4.1.1 PM and EPWI can be calculated from a sound pressure measurement when in the far field and a plane wave is a suitable approximation.

Determine the wavelength of the lowest frequency of interest (Equation 32) and the waveguide cut off frequency (Equation 33):

$$\lambda = \frac{c_{\mathrm{w}}}{f}$$ Equation 32

$$f_0 = \frac{c_{\mathrm{w}}}{4D\sqrt{1-\left(\frac{c_{\mathrm{w}}}{c_{\mathrm{b}}}\right)^2}}$$ Equation 33

where

f_0 = cut-off frequency;
D = water depth;
c_{w} = sound speed in water; and
c_{b} = sediment sound speed.

For a rigid bottom ($c_b \rightarrow \infty$) the cut-off frequency occurs when $D = \frac{\lambda}{4}$, where λ is the acoustic wavelength (Jensen, 2011).

Different sand types, locations, and measurement difficulties make it impossible to give a high-fidelity value of c_{b} for any bottom type (including rock). However commonly used estimations of c_{b} are as follows:

- Sand c_{b} = 1.20 c_{w}
- Silt c_{b} = 1.05 c_{w}.

If the distance to the sound source is more than one wavelength of the lowest frequency and the lowest frequency is greater than the cut-off, then the magnitude (but not the direction) of particle velocity can be estimated to within an order of magnitude using Equation 34, acceleration using

Equation 35, displacement using Equation 36 and EPWI using Equation 37. These equations only apply to a travelling plane wave and not a standing wave or any other combination of plane waves. Therefore, the signal to noise ratio (SNR) must be high such that sounds from other sources are negligible. Caution should also be taken when near the surface or bottom because reflections and interference will impact the degree to which a plane wave can be assumed. The relationship between the distance to boundaries and the degree to which the plane wave approximation introduces errors in relation to direct measurement error requires further investigation and is a research area ripe for collaboration between biologists and acousticians. There are relatively few biological examples that fit these conditions because animals that are sensitive to PM tend to hear low frequencies with long wavelengths and most inhabit shallow or benthic habitats, however one example may be a pelagic fish in deep water hearing a distant airgun.

4.1.2 PM and EPWI can be calculated from a sound pressure measurement when in the hydrodynamic near field with spherical spreading and a monopole source.

A monopole (point source) is a reasonable approximation for a source that radiates equally in all directions when the source is much smaller than the wavelength of the lowest frequency emitted (ka << 1 and kr << 1, where k = 2π/ λ and a = source size [Russel et al., 1999]). The hydrodynamic near field is the area closer to a monopole source than one wavelength. If the source type is a monopole and the distance to the sound source is less than one wavelength using the lowest frequency, we recommend measuring PM and comparing measurements with the calculated PM using Equation 38, Equation 39, or Equation 40 detailed in Section 4.2. Equation 42 shows how to calculate intensity from measured sound pressure and measured velocity, which can be compared with EPWI calculated from sound pressure measurements alone with Equation 37.

4.1.3 PM should be measured when in the geometric near field with a source that is not a monopole.

The geometric near field is the area that is either closer to the source than 5L (where L = source size in m), or in the Fresnel near-field (i.e., the source type is not a monopole and the distance to the sound source is smaller than $\frac{L^2}{\lambda}$, where r = distance (m) to the source, L = source size (m), λ = wavelength of highest frequency (m) (IEC 60565 of the International Electrotechnical Commission (IEC)). The geometric near field means that the distance to the source cannot be considered a constant. In this situation, waves from different parts of the source will contribute with different amplitudes and with fluctuating phase difference, violating the plane wave or spherical spreading assumptions for a monopole source, therefore we recommend measuring PM directly.

4.1.4 PM should be measured when below the cut-off frequency of the waveguide.

Below the cut-off frequency, sound waves will not propagate to long distances along a waveguide formed by the bottom and the surface (or the tank walls if in a tank). Close to the source and far from the boundaries the sound will propagate as spherical spreading. If the lowest frequency is below the waveguide cut-off frequency (see Equation 33) we recommend measuring PM due to the complex sound field.

While these criteria are grounded in the theory of physics, the best way forward is to perform sound pressure and PM measurements and compare them with calculations of PM whenever possible, to advance our understanding of when a plane wave is a suitable approximation.

4.2 How to calculate particle motion and EPWI from sound pressure measurements from a single hydrophone

When a travelling plane wave is a suitable approximation (see Section 4.1), sound pressure measurements from a single hydrophone can be used to calculate velocity using Equation 34, acceleration using Equation 35, displacement using Equation 36, and EPWI using Equation 37. Equations are shown in Table 2.

In the hydrodynamic near field of a monopole, far from any boundaries, sound pressure measurements from a single hydrophone can be used to calculate velocity using Equation 38, acceleration using Equation 39, displacement using Equation 40, and EPWI using Equation 37. Fourier transforms can be used to transform data from the time domain to the frequency domain, while inverse Fourier transforms can be used to transform data back from the frequency domain into the time domain. It is not possible to estimate any directional components of the PM or intensity vectors from this method alone.

See Appendix A for the definitions of the terms used in these equations. These calculations must be performed using linear quantities not levels (dB values), linear quantities can be converted to levels using methods described in Chapter 11.

Table 2 Mathematical Formulas for quantities under different acoustic conditions.

Quantity	Time domain formula	Frequency domain formula	Equation number
Velocity as a scalar for a plane wave	$u(t) = \frac{p(t)}{\rho c_\mathrm{w}}$	$U(f) = \frac{P(f)}{\rho c_\mathrm{w}}$	Equation 34
Acceleration as a scalar for a plane wave	$a(t) = \frac{\mathrm{d}u}{\mathrm{d}t}$	$A(f) = 2\pi\mathrm{i}f\ U(f)$	Equation 35
Displacement as a scalar for a plane wave	$\delta(t) = \int u\ \mathrm{d}t$	$\Delta(f) = \frac{U(f)}{2\pi\mathrm{i}f}$	Equation 36
Equivalent plane wave intensity (EPWI, a scalar)	$I_\mathrm{eq} = \frac{\overline{p^2}}{\rho c_\mathrm{w}}$	-	Equation 37
Velocity as a scalar for a spherical wave	$u(t) = -\frac{1}{\rho}\int \nabla p\ \mathrm{d}t$	$U(f) = \frac{P(f)}{\rho c_\mathrm{w}}\left[1 + \frac{\mathrm{i}\lambda}{2\pi r}\right]$	Equation 38
Acceleration as a scalar for a spherical wave	$a(t) = -\frac{1}{\rho}\nabla p$	$A(f) = 2\pi\mathrm{i}f\ \frac{P(f)}{\rho c_\mathrm{w}}\left[1 + \frac{\mathrm{i}\lambda}{2\pi r}\right]$	Equation 39
Displacement as a scalar for a spherical wave	$\delta(t) = \int u(t)\ \mathrm{d}t$	$\Delta(f) = (2\pi\mathrm{i}f)^{-1}\ \frac{P(f)}{\rho c_\mathrm{w}}\left[1 + \frac{\mathrm{i}\lambda}{2\pi r}\right]$	Equation 40
Active intensity as a scalar		$I(f) = \frac{\lvert P(f)^2 \rvert}{2\rho c_\mathrm{w}}$	Equation 41
Intensity as a vector using measured PM	$\boldsymbol{I}(t) = p(t)\boldsymbol{u}(t)$		Equation 42

4.3 How to calculate particle motion and intensity from pressure gradients measured with a hydrophone array

Whether plane wave or monopole approximations apply or not, multiple sound pressure measurements (pressure 'gradients', or 'differentials' – Equation 43 in Table 3) can be used to calculate particle acceleration via Equation 44, particle velocity via Equation 45, and particle displacement via Equation 46, provided the sound pressure measurements contain both magnitude and phase components (using the complex numbers produced by the Fourier transform, as described above in Section 4.2) (see Appendix A for an explanation of complex numbers and how to use them). The PM measured in this way is the component along the axis of separation of the hydrophones and its spatial resolution of the measurement is limited by the distance between the hydrophones. Therefore, it is possible to calculate vectors using this method (thus providing directional information) if an array of four or more hydrophones are arranged to capture the three orthogonal axes (x, y, z). These calculations must be performed using linear quantities not levels (dB values). Linear quantities can be converted to levels using methods in Chapter 11. Considerations for hydrophone arrays are given in Section 7.2.2. Time domain equations are in table 2.

Limitations

Adequate measurements of pressure gradients are subject to adequate temporal synchronisation of sound pressure recordings, hydrophone placement, hydrophone calibration, noise, flow, and hydrophone acceleration sensitivity. Inadequacies in measurement methodologies may lead to error (Gray et al., 2016).

At low frequencies (10 Hz) the sensitivities of the hydrophones may not be known precisely enough to produce a significant difference in their outputs. This introduces noise, removal of this noise can be achieved by filtering out the lower frequencies.

The electrical noise of hydrophone preamps becomes a consideration with low amplitude signals. The sensitivity of the hydrophone pair is markedly lower than the individual hydrophone sensitivities that form the pair.

Criteria

- Separation of the hydrophones (h) should be around ten times smaller than the shortest wavelength of interest (λ). This is because the error in measured intensity resulting from the sound pressure differential approximation may be less than 5 % for plane waves (corresponding to an error in measured level of less than 0.2 dB) provided that $h < \lambda/(3.7\pi)$ (Fahy, 1977). Further, some investigations suggest that $h < \lambda/4$ may be appropriate and when the wavelength is shorter than this constraint, the phase difference between hydrophones becomes ambiguous (Martin, unpublished data). For example, hydrophones should be less than 50 cm apart to provide an upper cut-off frequency of ~750 Hz.
- The accuracy of the time-averaged sound pressure differential is dependent on the accuracy of the temporal resolution of the sound pressure recordings. It is necessary for signals to be time synchronised by recording onto a single device. Internal clocks on different devices differ, clock drift, therefore synchronisation requires the use of a single recording device.
- Phase calibration: The hydrophones must also be far enough apart that the change in phase of a wave at the lowest frequency of interest as it travels between the hydrophones is more than the phase uncertainty of the hydrophones. Hydrophones that are calibrated to within 1 degree in phase will have a minimum frequency detection ability of 10 Hz.

- If wavelength (λ) is much greater than the separation of hydrophones (h) the sound pressure difference over such a small change in the wave's period would be below the level of accuracy possible from the hydrophone pair due to errors introduced by other means. In realistic terms due to the scale of possible separation of hydrophones (>0.5 cm) resulting from the physical space the hydrophones take up, and wavelengths in water, this relates to infra-sound (below 1 Hz).

Table 3 Mathematical Formulas for calculating PM quantities from sound pressure differentials.

Quantity	Formula	Equation number
Pressure differential approximation (h = hydrophone separation)	$\nabla P(f) = \frac{P_1(f) - P_2(f)}{h}$	Equation 43
Acceleration	$\boldsymbol{A}(f) = -\frac{\nabla P(f)}{\rho}$	Equation 44
Velocity	$\boldsymbol{U}(f) = -\frac{\nabla P(f)}{2\pi i f \rho}$	Equation 45
Displacement	$\boldsymbol{\Delta}(f) = -\frac{\nabla P(f)}{(2\pi i f)^2 \rho}$	Equation 46

4.4 Limitations on measurement of particle motion

- Motion sensors must be small (< one tenth of the shortest wavelength scale expected, which may be much smaller than the acoustic wavelength (Gray et al., 2016)).
- As with sound pressure, the measurement of PM is specific to the location of measurement in non-simplified acoustic conditions. Close to boundaries, there may be an acoustic near-field (which rapidly decays in a frequency dependent way with distance). Near field effects may cause rapid changes in PM over short distances. Therefore, there is a limitation to the space over which a point measurement can be considered to be relevant, depending on the acoustic conditions.
- PM sensors that directly measure particle velocity or acceleration must be designed such that they do not have a response to sound pressure.
- PM sensors must be sufficiently sensitive to PM that the electrical noise floor is at least 10 dB below the signal levels of interest.
- There is a trade-off between buoyancy of the sensor, electrical noise, and mechanical noise affected by the suspension system.
- Instrumentation for measurement of PM is discussed in more detail in Chapter 7.

4.5 Checklist

Requirements

- Report PM or intensity using one of the methods in this section when they are biologically relevant (see Section 1.3).
- If calculating PM or EPWI from sound pressure measurements from a single hydrophone while in the near field, check that a monopole is a suitable approximation (see Section 4.1).
- If calculating PM or EPWI from sound pressure measurements from a single hydrophone, check that a plane wave is a suitable approximation (see Section 4.1).
- If using sound pressure differentials to calculate PM or intensity, check hydrophone separation, calibration, and temporal synchronisation of recordings (see Section 4.3).
- If measuring PM with an accelerometer (or other PM sensor), check that the sensor is small relative to the wavelength of the highest frequency to be measured (Section 4.4).
- Collaborate with experts in the fields of biology, underwater acoustics, and PM sensors.

Recommendations

- If a plane wave or spherical spreading from a monopole source are not suitable approximations, measure PM using either the pressure gradient method, an accelerometer or other PM sensor.
- Calculate the intensity as the sound pressure and velocity product if PM has been measured.

5 How to Measure Sound Pressure

5.1 Measurement of sound pressure

In this section, key details of how to measure sound pressure are discussed, because of its relevance to calculating PM and sound intensity and because sound pressure measurements are always recommended alongside measurements of PM. Also discussed are important details on system components and their requirements, which are relevant to systems that measure PM using accelerometers, geophones, and hydrophone arrays. For a more detailed guide on good practice for underwater measurements of sound pressure refer to NPL (2014).

5.2 Hydrophones

A hydrophone responds to pressure fluctuations in the water and is designed as a sensor for sound pressure (IEC 60500:2017). Typically, a hydrophone uses a piezoelectric sensing element which produces an electrical voltage across its terminals in response to the action of the sound pressure in the acoustic wave (occasionally, hydrophones are designed to be charge sensitive devices which develop an electrical charge in response to the sound wave). A hydrophone must be calibrated for its signals to have absolute meaning and the calibration must be traceable to national or international standards and conform to IEC 60565 (IEC 60565-1:2020, IEC 60565-2:2019). The sensitivity of a hydrophone is typically expressed at a succession of discrete frequencies, or in the form of a calibration curve, in units of volts per pascal, V/Pa (for a charge sensitive device, the units are coulombs per pascal, C/Pa). If expressed as sensitivity level in decibels, the reference value of sensitivity is 1 V/µPa (IEC 60500:2017; IEC 60565:2020). The addition of extra cable reduces the overall sensitivity for hydrophones without a built-in pre-amplifier; however, this will not affect the sensitivity of hydrophones with built in pre-amplifiers. The reduction of sensitivity of the extension cable shall be characterised to correct the data before analysis (for guidance see IEC 60565-1:2020).

5.3 Instrumentation and measuring system

All aspects of the measuring system apart from the hydrophone are also relevant to systems used for measuring PM. Therefore, refer to Chapter 7 on Instrumentation for details of the additional system components.

5.3.1 Components

The measurement system consists of hydrophone(s), conditioning preamplifier(s), analogue-to-digital converter(s), and a computer (ISO 18406:2017). The measuring system may consist of individual components or as an integrated system such as an autonomous recorder that provides a self-contained recording system powered by batteries (ISO 18406:2017). The main components are listed in bold.

Amplifiers

These increase the signal's amplitude to levels appropriate for the next processing steps (NPL, 2014).

Filters

A filter defines a range of frequencies of a signal which can pass through to the rest of the system and rejects frequencies outside of this range. Filters are typically known as low pass, high pass or bandpass depending on their frequency response. By definition, a filter response varies with frequency, and shall be characterised over the full operating frequency range of the system (IEC 61260-1:2014).

Analogue to Digital Converter (ADC)

An ADC (sometimes known as a digitiser) is used to convert an analogue signal into a digital format. The ADC sensitivity is normally expressed as a scaling factor calculated from a ratio of output voltage to input voltage (NPL, 2014). See Section 7.5 for more information on ADCs.

Data storage

Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data (NPL, 2014). For guidance on data storage, see Chapter 7.

5.3.2 Key performance characteristics

System sensitivity ('end-to-end calibration')

For digital systems, the system records the sound as a digital waveform via an ADC and does not provide an analogue voltage output. The calibration of the ADC is incorporated into the overall sensitivity of the whole system including the ADC. This may be termed the digital system sensitivity, which is the number of digital counts per unit change in sound pressure (unit Pa^{-1}). Sometimes, the digital system sensitivity may be represented as a scaling factor by which the digital waveform values must be multiplied to obtain sound pressure values in pascals (this is equivalent to the reciprocal of the digital system sensitivity).

Definitions of system sensitivity are provided by ISO 18406 (ISO, 2017), ADEON (Ainslie et al., 2020), and the JIP source characterisation standard (de Jong et al., 2021)

System calibration

The whole measuring system shall be calibrated over the full frequency range of interest (Hayman et al., 2017). This includes the hydrophone, amplifier, filter, cables, and ADC. It is preferred that a full laboratory calibration is performed at a minimum of every 2 years (preferably more frequently), with a check calibration before deployment and after retrieval (see 'Field calibration checks' below). The calibration of the hydrophones shall be traceable to national or international standards and conform to IEC 60565 (IEC 60565-1:2020, IEC 60565-2:2019).

Hydrophone sensitivity

The sensitivity of the hydrophone shall be appropriate for the amplitude of the signal to be measured to avoid nonlinearity and system saturation (i.e., clipping) by high amplitude signals. For high signal levels, a relatively low sensitivity hydrophone and system is recommended (hydrophone sensitivity level (re 1 V/µPa) less than -205 dB) for use at a minimum range of 1 km from high amplitude impulsive sources. For ambient or background noise measurements, where a low self-noise performance and high sensitivity is generally required, a hydrophone sensitivity level (re 1 V/µPa) of -185 to -165 dB is recommended.

Frequency response and sampling frequency

The frequency response of the whole measuring system shall be set to a range sufficient to cover all frequency components of interest within the measured signals (IEC 60500:2017; ISO 18406:2017). At minimum, the system frequency bandwidth shall cover between 10 Hz – 20 kHz, with a minimum sampling frequency of at least 44.8 kHz to capture upper band limit of 22.39 kHz for the 20 kHz one-tenth decade (decidecade) band. However, when the hearing response of relevant biological receptors extends to higher frequencies, a higher sampling frequency may be required (ISO 18406:2017). It is desirable that the system sensitivity be invariant with frequency over the frequency range of interest to within a tolerance of 2 dB. An anti-aliasing filter may be used to remove low frequency artefacts caused by signals of frequency higher frequency than half the sampling frequency, and this may reduce the usable bandwidth. See Section 7.5 for more information on anti-aliasing filtering.

Directivity

The hydrophone used shall have an omnidirectional response such that its sensitivity is invariant with the direction of the incoming signal to within a tolerance of 2 dB (at least in the azimuth orientation) over the frequency range of interest.

System self-noise and signal to noise ratio

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

Dynamic range

Dynamic range is the measuring system’s effective amplitude range over which the system can faithfully measure the sound pressure. The dynamic range quantifies the ability of a system to capture signals from the lowest to the highest signal amplitudes without distortion. This can be expressed in decibels representing the difference between the lowest and highest amplitude level of signal. The highest possible non-distorted amplitude is the amplitude of the ADC’s full-scale signal (i.e., its maximum unclipped amplitude), while the lowest possible non-distorted amplitude is determined by the size of the ADC’s quantisation step. System dynamic ranges in excess of 60 dB are preferred for measurement of high-power impulsive sound sources. As a minimum, data shall be recorded in resolution no less than 16 bit in the ADC stage, with an associated ADC dynamic range of 96 dB when limited by quantisation noise. However, a 24-bit ADC with dynamic range of 144 dB is desirable. A system dynamic range of 144 dB would normally not be achievable because this is limited by the system self-noise and the maximum measurable undistorted signal.

Field calibration checks

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

- Hydrophone calibrator, consists of an air pistonphone that generates a known sound pressure level at a defined frequency inside a coupling chamber into which the hydrophone is inserted. Note that this method generally provides a field calibration check at only one frequency (typically 250 Hz) but it allows the integrity of the entire system to be checked (ISO 18406:2017). A recorded pistonphone signal is also a good check for use with analysis scripts and provides a check on the previously mentioned conversion of digital waveform to sound pressure.
- An electrical check calibration of the system components. If the hydrophone has an insert voltage capability, electrical calibration can be performed through voltage injection that checks the system electrical integrity. However, it does not perform an acoustical check on the hydrophone element. (NPL, 2014)

Autonomous recorders

If the hydrophone is placed close to a physical structure (for example, physically attached to the body of a recorder), the scattered sound may interfere with the direct sound wave and cause perturbations in the frequency response and directivity at kilohertz frequencies. In addition, for a recorder with the hydrophone attached to the body, resonances in the body of the recorder may give rise to fluctuation in the response in the range 500 Hz to 1 kHz (ISO 18406:2017; Hayman et al., 2017; NPL, 2014).

A summary of nominal recommended performance specifications is provided in Table 4.

Table 4 Recommended sound pressure recording system performance specifications.

Performance Characteristic	Nominal Recommended Specifications	
	High amplitude impulsive sound	Ambient / low amplitude sound
Sensitivity level (re 1 V/µPa):	Less than -205 dB (For use at typical ranges of 500 m to 2 km)	Between -185 to -165 dB
Frequency range:	Nominal 10 Hz – 20 kHz (For decidecadal analysis, frequency range needs to include the limits of the 10 Hz and 20 kHz decidecade (one-tenth decade) bands.	
Frequency response	Invariant with frequency (flat response) in the range 10 Hz to 20 kHz decidecade bands (To a tolerance of ±1 dB)	
Sampling rate:	40 kHz minimum (Or at least 44.8 kHz to include 20 kHz decidecade band)	40 kHz minimum (Or at least 44.8 kHz to include 20 kHz decidecade band)
Directionality:	Omnidirectional to within +/- 2 dB up to 20 kHz	
System self-noise and signal-to-noise ratio	Self-noise ideally 6 dB below the lowest sound level giving minimum SNR of 6 dB	
Dynamic range:	System dynamic range in excess of 60 dB is preferred. Analogue to digital converter (ADC) Minimum 16 bit resolution (ADC dynamic range 96 dB), Preferable 24 bit resolution (ADC dynamic range 144 dB)	
Filtering:	Any filter characteristics should be known, and corrections applied (low pass and high pass filtering caused by instrumentation). Any low frequency roll-off in recorder performance due to high pass electronic filtering shall be measured so that suitable corrections can be applied. For peak sound pressure estimation of pulsed signals, the phase response may be important.	
Calibration	Laboratory calibrated to traceable standard within the last 2 years. Field calibration before deployment and after retrieval.	

The recommended specifications shown in Table 4 are provided for general guidance and represent typical values of sensitivity that are generally suitable for measurement of both high amplitude sources and for ambient sound. For the impulsive sources, a case-by-case assessment is needed of the likely sound pressure at the measurement location in order to set the overall system sensitivity low enough that the signal level does not exceed the maximum recordable value (so that there is no clipping or distortion) and high enough that the signal-to-noise ratio is sufficient. The maximum sound pressure values can be estimated by consideration of the maximum values of the typical source level of the source (estimated from scientific literature) and the signal attenuation due to propagation from the source to receiver (the latter may be estimated crudely using simple spreading models and absorption). It is better to err on the low side with the system sensitivity (clipping or distortion of the signal is a worse error than a degraded SNR. The choice of –205 dB for sensitivity level (re 1 V/µPa) is generally suitable for measuring sound from sources whose source level (re 1 µPa m) is 220 dB at ranges from about 500 m to 2 km. However, measurements are not limited to this range. For example, for the same source, a system with a hydrophone sensitivity of -205 dB, with max input voltage of ±5 V, will clip at a sound pressure amplitude of 89 kPa, at a distance far less than 500 m. At greater ranges, the system gain can be increased to amplify the signals, but this also increases the background noise. Ideally, a hydrophone with greater sensitivity would be used to maintain the SNR.

5.4 Deployment types

5.4.1 Static deployment

A static deployment typically consists of hydrophone(s) connected to an autonomous recorder that can be moored at the bottom of the seabed to allow remote acoustic measurement in the water column (Figure 5). This system enables multiple units to be deployed at the same time in order to monitor the sound propagation at several fixed ranges simultaneously. This is considered a cost-effective method for measuring underwater explosions if multiple ranges are required. It also allows a combination of measurement modalities: a hydrophone may be combined with a PM sensor in the same autonomous logger unit. Field deployment of a static system is typically more complex than a vessel-based deployment, as it requires a mooring to be built and prepared prior to the field trial. To deploy and retrieve equipment to the seabed, a surface buoy can be used as a surface marker such as the hydrophone deployment of Figure 5c. However, such a deployment is attractive for fisherman or other seafarers to steal the equipment. To reduce the likelihood of equipment being stolen, commercially available release transponders provide a useful means to deploy items to the seabed without a visible surface buoy. Recovery requires connection to a seabed anchor with an acoustic release system, which enables the recorder to be hauled to the surface. However, this does not completely prevent equipment being trawled or otherwise lost, which is otherwise an important consideration to make.

A static deployment may also consist of a fixed hydrophone which is permanently deployed and cabled back to a shore-based measuring station. Such a system is preferable for long-term deployments in specific locations and has the advantage that a continuous stream of data may be recorded without the need of duty-cycles for battery operated archival recorders to limit power consumption and extend battery life. However, unlike for portable recorders, the measurement location is fixed and cannot easily be moved.

5.4.2 Vessel based deployment

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

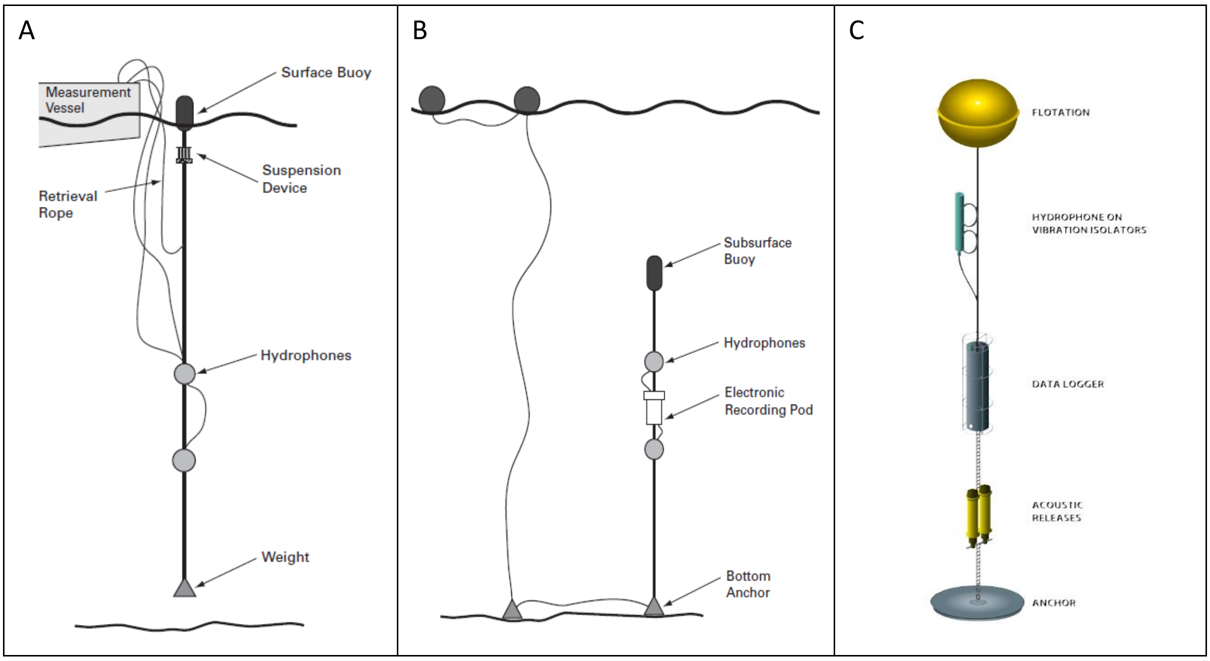


Figure 5 Examples of deployment strategies for hydrophones and recorders.

5.4.3 Platform noise

Deployments can suffer from certain types of platform-related noise (ISO 18406:2017) such as:

Acoustic self-noise:

Cable strum

Noise caused by the action of current on the taut cable. Any resonances in the cable or support should be avoided. The use of fairings may reduce the effect of cable strum by mitigating vortex shedding.

Vessel noise

This can be any source of noise originated from survey vessel, sources include the engine propeller, generator, echo sounder and other vessel machinery.

Mechanical noise

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

Non-acoustic self-noise

Flow noise

Low frequency noise caused by the turbulent flow around the hydrophone.

Surface heave

Large amplitude, low frequency noise caused by the changes of hydrophone depth due to vertical motion of wave action.

Electrical noise

Typically caused by the measuring system being powered by a vessel electrical main, causing electrical interference and noise.

General considerations

With regard to platform noise, a static bottom-mounted deployment is generally preferable to a surface deployment because the hydrophone is positioned away from the air/water boundary, thus minimising the effect of this pressure-release boundary on the sound field and reducing parasitic signals from the influence of surface wave action. It also has the advantage that measurements may safely be made at range that is considered unsafe for vessels during an offshore operation. In addition, a human presence is required for a vessel-based deployment, and this may not be possible if there is a safety exclusion zone around the source, or if long-term monitoring is required.

For measurements made of a benthic habitat, a hydrophone is best positioned in the lower half of the water depth and at least 2 m above the seafloor. If hydrophones are to be deployed at two depths, these should be placed in the lower half of the water column ideally between ½ and ¾ of the total depth, ideally with the separation between hydrophones maximised. When marine fauna of interest resides in the upper half of the water column, the hydrophone(s) may be placed in the upper half of the water column.

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, thereby reducing flow 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 global positioning system (GPS) receiver is sometimes used to provide a log of positional data. Such a system is not suitable for long-term deployments.

5.5 Checklist

Requirements

- Choose a hydrophone and measuring system with appropriate performance considering frequency response, directivity, dynamic range, self-noise (Section 5.2)
- Use a calibrated hydrophone and system over the frequency range of interest with the calibration traceable to recognised standards. (Section 5.2)

Recommendations

- Minimise platform noise in deployment of hydrophones and recorders (Section 5.3)

6.1 Introduction

For fishes and invertebrates that live in the water column and on or close to the seafloor, seabed vibrations influence the soundscape. Seabed vibrations may be sensed directly or they may cause sound to be radiated into the water column. Seabed vibration measurements are taken against a backdrop of the earth's natural vibrational noise (< 10 Hz) and the electrical noise from measurement devices. This section describes the principles of seabed vibrations and their measurement. The reason for mentioning such low frequencies is because these frequencies are ubiquitous the world over and they overlap in frequency range (at the high frequency end, between 0.1-10 Hz) with acoustical measurements reported in the 1960s (Wenz, 1962) and in the 2010s (Prior et al., 2012).

6.2 Earth's background vibration

Earth has a background level of low frequency excitation in the form of microseisms (Shearer, 1999). These are naturally occurring vibrations in the Earth's crust. The Earth's crust is coupled with ocean-going gravity waves whose power spectral densities change dramatically across the periods from 1,000 seconds to 1 second. Ocean waves incident on coasts generate seismic surface waves via three pathways: direct pressure on the seafloor (primary microseisms), standing waves from interaction of incident and reflected waves (double-frequency microseisms), and swell-transformed infragravity wave interactions (the Earth's seismic hum) (Traer et al, 2012).

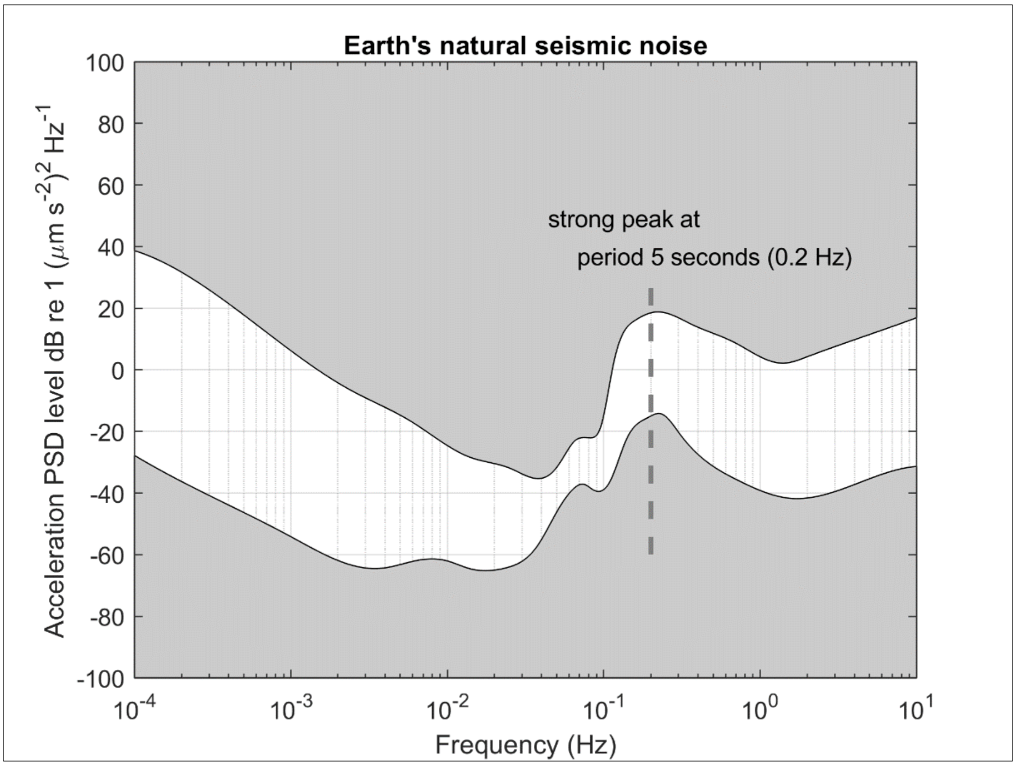


Figure 6 Earth's natural seismic noise.

Figure 6 shows the acceleration PSD levels of typical measurements in the absence of large seismic events. As can be seen in Figure 6, there is a peak at 0.2 Hz (a period of 5 seconds) reported at most measurement sites (Shearer, 1999). The frequency of Earth's lunar tide is 22.2 μHz, so there is naturally another peak in acceleration PSD level to the left of the graph in Figure 6 slightly below the minimum frequencies plotted. Furthermore, the Earth's rotation occurs at 11.6 µHz. Systems that are able to measure the rotation of the earth are able to gyrocompass, which is to say that they can determine their bearing without the need for measurement of the earth's magnetic field. However, orientating the axes of a PM sensor on the seabed is typically done using both the acceleration due to gravity and the earth's magnetic field.

Acoustic waves in sea water are able to penetrate below the seabed, especially at low frequencies. At low frequency these wavelengths are long, so the penetration depth is deep into the seafloor sediments. Because acoustic propagation interacts with the seabed to a great extent at low frequency, the acoustic waveguide at low frequency cannot be addressed without considering seabed vibration (Wilcock et al., 2014). The coupling of the propagation in the seabed combined with the acoustic propagation in the water column, creates an equivalent ocean waveguide with pressure release boundaries, whose effective depth can be calculated (Weston, 1960; Chapman et al., 1989; Zhang and Tindle, 1993).

6.3 Interface waves

The seabed and surface are areas where the sound pressure and particle velocity may not follow Chapter 3's Equation 9 describing the simple relationship between particle velocity and sound pressure. The sea surface resembles a free boundary, at which the sound pressure is zero and the PM is maximal. A free boundary is a perfect reflector, with an incident sound pressure wave undergoing a π phase change. At the opposite extreme, consider a perfectly rigid (immovable) boundary, at which the PM is zero and the sound pressure is maximal. A rigid boundary is also a perfect reflector, albeit with zero phase change. At the sea surface (a pressure-release boundary), there is therefore a zone very near the surface with minimal sound pressure signal, the size of which depends on frequency. Near-rigid boundaries are less common due to the prevalence of sediments on the ocean floor. However, the increased impedance at the ocean floor appreciably reduces the PM and correspondingly increases sound pressure. To know the precise PM near the surface or seabed, it is recommended that *in situ* measurements be performed (Nedelec et al., 2016). The increased seabed sound pressure is measurable with standard hydrophones.

For angles of incidence that are off perpendicular, and for real seabeds that are not perfectly rigid, the reflection and transmission coefficients depend on the density and sound speed in the water (ρ_1, c_1) and sediment (ρ_2, c_2) as well as the angle of incidence (Figure 7 Sketch of the bottom interactions for sound emitted by a point source. , see also Jensen et al. (2011) Section 1.6). At low incidence angles (high grazing angle, for paths steeper than the critical angle) part of the sound energy is reflected back into the water, and part is transmitted into the seabed where it can then penetrate or reflect off deeper layers (e.g., ρ_3, c_3) and return to the water column. Stoneley waves and Love waves can exist at the interface between two solids such as the deeper layers of the seabed so may need to be considered when modelling sound propagation between the seabed and the water column (Morfey, 2000).

Beyond the critical incidence angle for the seabed, all of the sound is reflected back into the water column by total internal reflection (grey line in Figure 7). At the critical incidence angle, which is given by $\theta_{\text{crit}} = \sin^{-1}\left({}^{c_1}/_{c_2}\right)$, the transmitted wave travels directly along the sediment-water interface at speed c_2; this wave is known as a head wave. It remains a longitudinal wave where the particles oscillate back and forth in the same direction as the propagating energy. The head wave arrives before the direct path sounds when $c_2 > c_1$ and seabed conditions support long-range propagation. Head waves are often encountered when seismic surveys occur over flat sandy seabeds in water depths up to several hundred metres. The head wave amplitude is attenuated by ${}^{1}/_{r^2}$

($40\log_{10} r$ in decibels) (Bevans and Buckingham, 2017), by frequency dependent absorption in the sediment, and by scattering due to seabed roughness, which strip away high-frequency content (> 10 Hz) of the signal with range. The sound speed in the sediment can be determined numerically from the difference in arrival time between the direct path and head wave if the range to the source, source depth, and water depth are known.

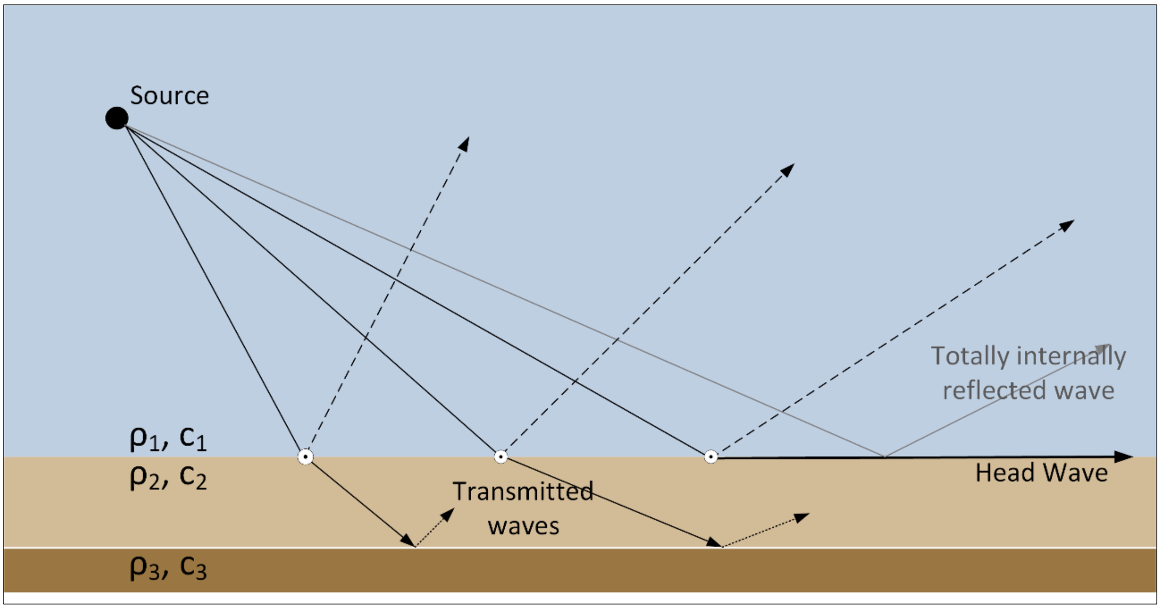


Figure 7 Sketch of the bottom interactions for sound emitted by a point source.

In discussions of the possible effects of sound on benthic animals, seabed motion is a specific concern (Hawkins et al., 2021). For example, a Scholte wave is an interface wave that propagates between the water and sediment. This is a transverse wave that displaces the solid surface vertically as the wave moves along the interface, causing an elliptical particle motion near the seabed. The penetration of the wave into the solid is in the order of $1/\lambda$, where λ is the wavelength. Small-scale Scholte waves are employed by seismologists to interpret the characteristics of the first few 100 m of the seafloor by measuring the wave's dispersion and attenuation. The experimental waves are generated by dropping a weight onto the seafloor or generating an impulse near the seafloor using an explosive or airgun. The coupling of these impulses decreases as $1/h^2$ where h is the height of the source off the seabed (Zhu and Popovics, 2006). Scholte waves typically have speeds below 300 m/s, only contain frequencies below 20 Hz and only propagate for a few kilometres (e.g., Schirmer, 1980, Bibee and Dorman, 1991). Thus, seismic airgun surveys only generate Scholte waves when the source is deployed close to the seabed (e.g., < 10 m) and the waves will be measurable within several km of the seismic source. If Scholte waves are generated by a seismic survey, they can be detected in a waterfall plot as a slower moving wave than the main waterborne arrival (Hovem, 2014; Hovem et al., 2012).

The effect of seabed waves on acoustic propagation in shallow water can be modelled by considering shear waves (Ellis and Chapman, 1985) and inclusion of shear waves in the seabed can improve the accuracy of propagation modelling. Early efforts of combining hydrophone and geophone measurements were used to monitor the Mid Atlantic Ridge using a cabled system (McGrath, 1976). More recently, it has been found that existing communications infrastructure in the form of fiberoptic communications cables can be used to measure seabed vibration (Marra et al., 2018).

6.4 Practical coupling to the seabed

PM on the seabed combines both seabed vibration and acoustic PM. It can be measured using either geophones or microelectromechanical system (MEMS) accelerometers. The ability to couple acoustic instruments to the seabed depends on seabed type (see Chapter 5). The seabed is often covered by a veneer of soft silt. A geophone should make PM measurements of the underlying seabed and not the silt, where the sensor may undergo lateral slippage. A simple means of coupling sensors to the seabed is to drive a stake into the seabed and attach geophones to the stake. Another means is to tow sensors on heavy sledges or cables that sink into the silt. A sledge might be a suitable means to couple to a sand or mud bottom, whereas a benthic lander (a bottom moored all-in-one system) maybe required for gravel or rock. If a lander is used, the influence of the lander on any PM measurement may need to be taken into account based on the frequency of interest and any resonances in the lander.

For longer term measurements, cabled deployments allow power and communication to be provided to seabed instruments from shore or an observation station (Section 5.4.1). This type of deployment has the advantage of removing the constraints of battery power-budget to the measurement equipment and many PM sensors can be combined along a cable in an array. In one example of a cabled system, geophones and hydrophones can be towed into position in cabled arrays interconnected for power and communication to sensors. The cabled system with geophones would typically have a lower noise floor than battery powered MEMS devices. However, a battery-powered system may be attractive for its practicality and portability. More recently, the cabled technique has been largely superseded by ocean bottom nodal surveys, where seismic nodes can be placed with either remotely operated or autonomous vehicles (Romanowicz et al., 2006).

Note that sensors deployed to measure PM in the water column that are mounted on the seabed will need decoupling from the seabed vibrations. To do this, the coupling to the seabed needs to possess some compliance (flexibility) with a resonance frequency outside of the range of interest. Some techniques as described in Section 5.4.3 and 9.3.2 and in the references cited there.

6.5 Checklist

Requirements

- Determine whether the low frequency noise observed in a measurement is either physical or coming from self-noise in the instrument used.
- Choose an appropriate lander for the seabed type.

Recommendations

- Classify the seabed as sand, gravel, mud or rock.
- Choose a cabled or battery powered deployment according to the noise floor and signal of interest.
- Be aware that slowly-propagating seabed waves arise from shear moduli in the solid seabed and that this can lead to unexpected or additional times of arrival in acoustic signals.
- For low-noise seabed deployments, consider using the earths background low frequency noise as a means to check that the measurement follows the expected peak at around 0.2 Hz.

7 Instrumentation

In this chapter we discuss the details of instrumentation for PM measurements. First, we outline the components of entire measurement systems and some of their potential configurations. Then we distinguish between sensors that measure particle acceleration, pressure gradients, particle velocity and particle displacement. Due to their popularity, we focus in depth on the specifications of accelerometer-based sensors, then finally we cover the specifications of other components of a typical measurement system. Apart from the sensors themselves, many measurement system components will be similar to those used for measuring sound pressure and the reader is encouraged to refer to Chapter 5 where appropriate.

7.1 Measurement systems

A PM sensor system consists of several parts that must function together in order to provide reliable results. Figure 8 is a schematic of two potential system configurations using an accelerometer as the sensor (the sensor can be of some other type). The measurement configurations of the system can look very much like hydrophone systems on the market at the time of writing, see Chapter 5 for examples.

The sensor is usually attached inside a body for protection from the water and in order to reach suitable buoyancy. The material can be made out of polyvinyl chloride (PVC), syntactic foam or some other material. This body in combination with a sensor forms the PM sensor, from now on called PM sensor, since it is this combination that is exposed to the motion of the surrounding water.

The suspension system of a PM sensor forms an integral part of that sensor. Accelerometer and geophone-based PM sensors generally have a proof mass (a known quantity of mass) system in the sensor construction. Any suspension of the sensor will have a characteristic compliance that will affect the motion of the casing relative to the proof mass, making the method of PM sensor suspension an important part of the measurement system. It is important to calibrate the sensor with any suspension method used. Using the minimum suspension possible will maximise the sensitivity of proof mass-based systems, however a minimally suspended instrument will move in the water, creating additional challenges. See Chapter 8 for further details on PM sensor calibration.

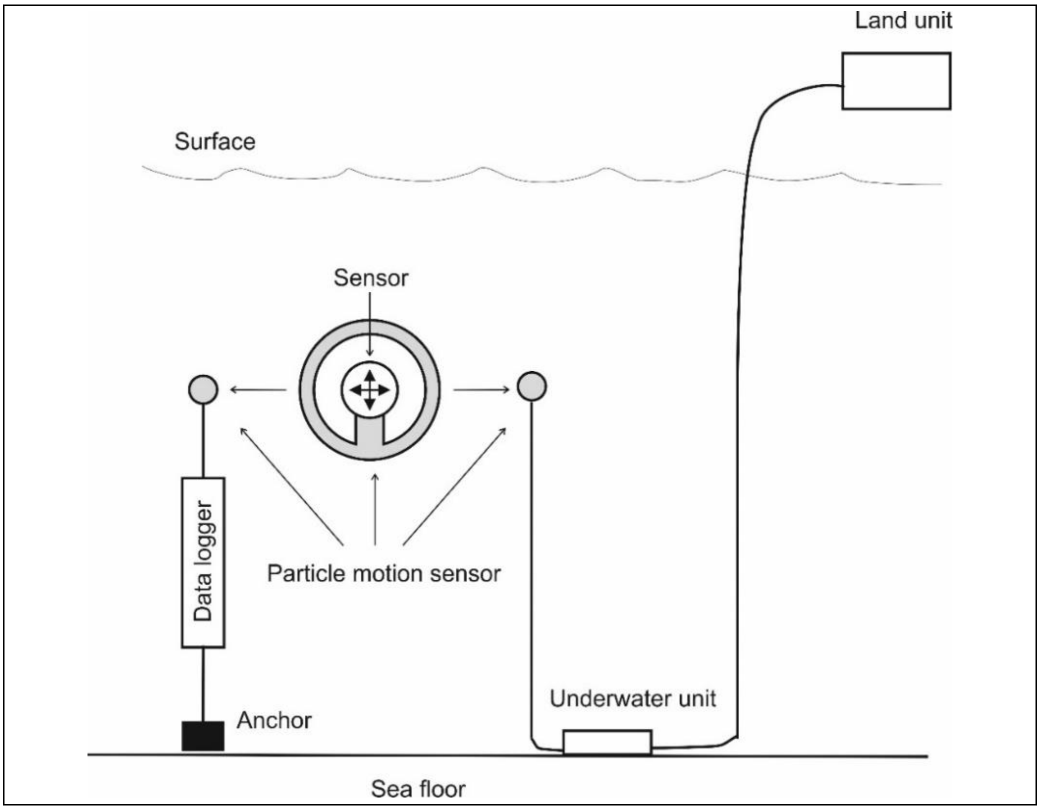


Figure 8 Schematic of the sensor suspended inside a hollow sphere with two alternative sensory system configurations. Left: An autonomous system. Right: Cabled system to surface/land. The particle motion sensor can have negative buoyancy making the suspension of the particle motion sensor simpler.

In order to measure directivity and intensity, a hydrophone on or close to the sensing head is needed. This is explained in greater detail in Section 7.3 under 'Directivity'.

Figure 9 depicts a system block scheme of an autonomous data logger configuration. The PM sensor detects motion, converts it to an electrical signal that is transmitted to the signal conditioning block. The signal conditioning unit amplifies and filters the signals if necessary. The ADC digitises the signal, which afterwards passes to a microcomputer that controls, among other things, timing and storage of the signals to a hard disk or secure digital (SD) card.

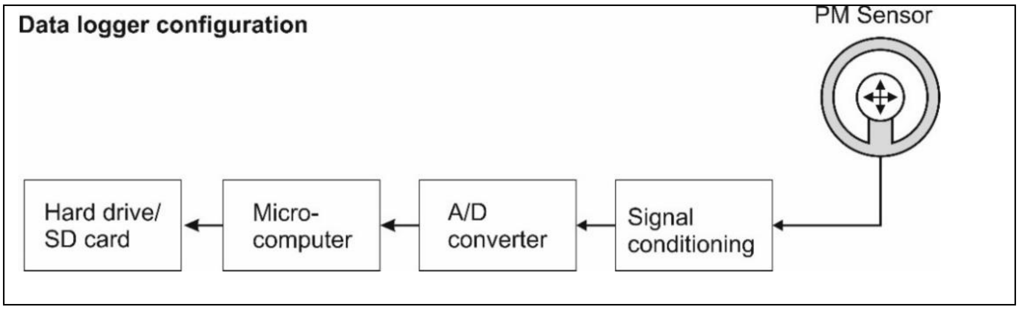


Figure 9 Data logger configuration as a block scheme.

Figure 10 shows a block scheme of a cabled configuration. The blocks are similar to the data logger configuration. The difference being that the cabled systems have the option to monitor data in real time. With a cabled system (especially with long copper cables) it is recommended to have a signal conditioning unit within a few metres of the PM sensor. If transmitting analogue signals over long cables there is a risk that electromagnetic background noise will be induced in the signal cables, decreasing the SNR. One way to counteract this effect is to include an amplifier close to the sensor that increases the SNR prior to transmitting signals to land/boat. An alternative option is to include an ADC close to the signal conditioning unit. Digital signals are robust against noise and can be transmitted over long distances. The maximum ethernet cable length, with standard copper wires, that can be used is 100 m. There is a possibility to increase the length with digital signal conditioners/repeaters at certain distances. Single mode fiber optical transmission gives the user the option to transmit Gigabit Ethernet signals over several tens of kilometres of cable length.

In the block scheme in Figure 10 the underwater unit contains the signal conditioning to ADC block. To power up the blocks one needs to relay power from land/boat into the unit and convert the power to suitable amplitudes.

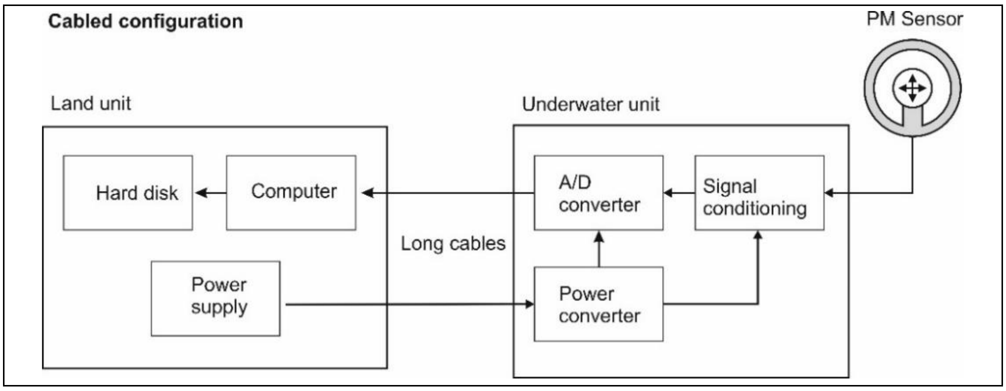


Figure 10 Cabled configuration as a block scheme.

In the following sections, a more detailed description of the blocks is given starting with sensors.

7.2 Sensors

There are several ways to measure PM in water, and correspondingly, several different types of sensors. Some available sensors are discussed in the sections that follow; examples are shown in Figure 11.

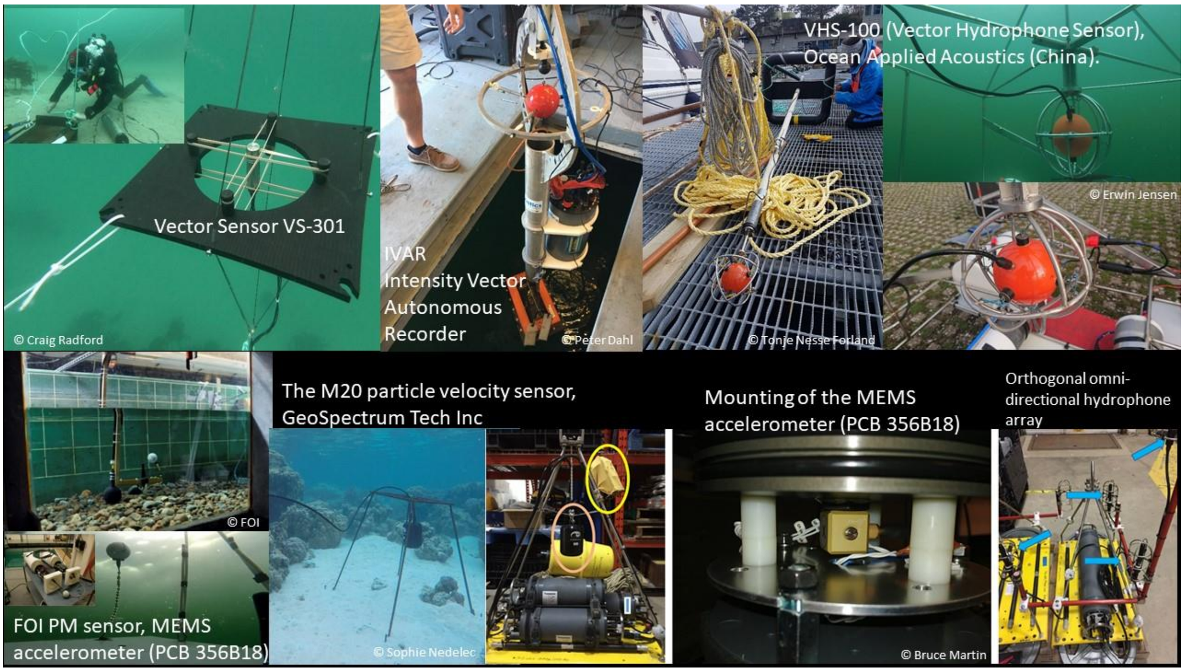


Figure 11 Examples of PM sensors in use at the time of writing.

7.2.1 Sensors that measure particle acceleration

Accelerometers

The traditional and most common PM-sensor configuration, when writing this document, is based on accelerometers (inertial sensors). The frequency bandwidth of sensitivity of accelerometers is from direct current (DC)to tens of kilohertz, depending on accelerometer type. DC measurements can be very useful since they show the direction of gravity.

The accelerometer technology front is moving rapidly forward. The classical accelerometer types are based on capacitive, piezoresistive and piezoelectric technology. There are other accelerometer technologies where the sensing elements are based e.g., in fibre optics or electron tunnelling. It is not possible to cover all technologies in this document so the focus here is on the classical types since these are the ones used frequently in PM sensors at the time of writing. All the classical types can be integrated in MEMS containing all the necessary components for tri-axial sensitivity in one convenient package. However, the packaging of sensors based on piezoelectric technology often consist of one (per axis) relatively large piezo element, i.e., not a MEMS package. One way to scale up the SNR is to have large elements. Accelerometers for seismic measurements may have a largest dimension of over 5 cm and have a weight of several hundred grams. Another way to increase the SNR is to increase the number of sensing elements. MEMS miniaturisation allows for smaller and smaller sensing elements as the manufacturing technology is progressing, increasing the possible number of elements in a given volume of space. Until the time of writing, large piezoelectric elements have the greatest sensitivity and SNR but the gap between these and MEMS accelerometers is narrowing. Capacitive sensors are especially simple to miniaturise relative to other types. All accelerometers using integrated circuits need some type of power supply. Below is a brief description of the functioning principle of the capacitive, piezoresistive and piezoelectric accelerometers.

Capacitive accelerometers.

See Figure 12 for a schematic of a capacitive accelerometer. If the accelerometer is moving, there is a displacement of the sensing elements from the equilibrium position. The capacitance is changed between the ‘freely’ moving mass and the electrode attached to the housing. The capacitance change is converted to a voltage signal in the electronics unit. This type of accelerometer is usually found in modern cell phones and similar. These have a small size but, historically, lower SNR than piezoelectric accelerometers and also the bandwidth has been limited to lower frequencies (1-2 kHz or so). As mentioned above, this is rapidly changing with improved technology. Capacitive accelerometers allow for DC measurements yielding information of the direction of gravity.

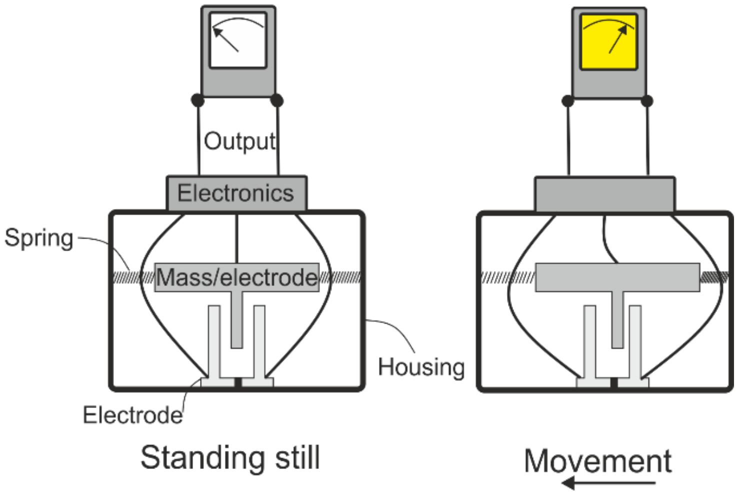


Figure 12 Schematic of a capacitive accelerometer. Left, accelerometer is in equilibrium (no motion). Right, the accelerometer is moving to the left and the mass is displaced relative to the housing. The capacitance between the mass and electrodes on the housing is proportional to the distance between them.

Piezoresistive accelerometers.

See Figure 13 for a schematic of a piezoresistive accelerometer. As the name implies, the sensing principle is the changing resistance of a piezoelement as it is subjected to bending. The electronics unit converts the resistance to a proportional voltage signal. As the accelerometer moves, additional bending is applied to the piezoresistor. This type of accelerometer is popular for measurement of high amplitude impulsive anthropogenic sound sources such as pile driving and airgun arrays. Piezoresistive accelerometers allow for DC measurements yielding information about the direction of gravity.

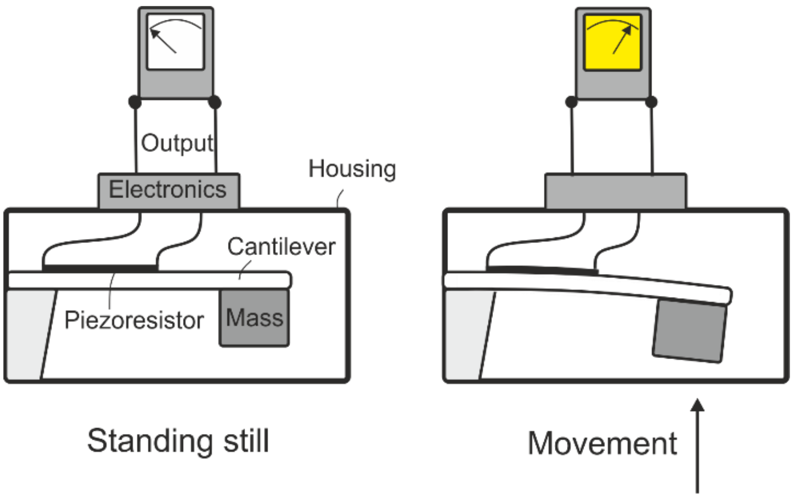


Figure 13 Schematic of a piezoresistive accelerometer. Left, accelerometer is in equilibrium (no motion). Right, the sensor housing is accelerating upwards and due to inertia, the mass is 'left behind' causing additional bending on the cantilever with the piezoresistor attached on top of it. The piezoresistors resistance varies with bending.

Piezoelectric accelerometers.

See Figure 14 for a schematic of a piezoresistive accelerometer. In standard configuration these use lead zirconate titanate (PZT) sensing elements (ceramic) giving good sensitivity and SNR. The ceramic is placed in between a mass and a base that is attached to the housing. When the accelerometer is moved, the ceramic is subjected to pressure which displaces the atoms in the crystal lattice structure. The displacement creates a potential difference in the ceramic which can be used by attaching conducting electrodes. The electrodes are attached to an electronics device where the charge level is amplified and converted to a voltage level.

Voltage mode internal electronic piezoelectric (IEPE) accelerometers are the simplest to use. i.e., the accelerometer comes in a complete package consisting of the piezoelectric elements together with the needed electronics. The drawback is that the signals may become saturated for a while if there is a (too) high amplitude input to the system. Also, these sensors usually allow measurements from 1 Hz and up, and do not allow for measurement of gravity.

Piezoelectric accelerometers can also be bought and used as charge mode devices. In this case the electronics unit is removed from the accelerometer package. These accelerometers are often used in hostile environments (e.g., heat or radiation). The signal cable has to be connected to an external charge amplifier and signal read out device. The (low noise) cabling has to be performed carefully and accurately due to the high impedance charge signal. The advantage is that the accelerometer itself does not need an external power supply.

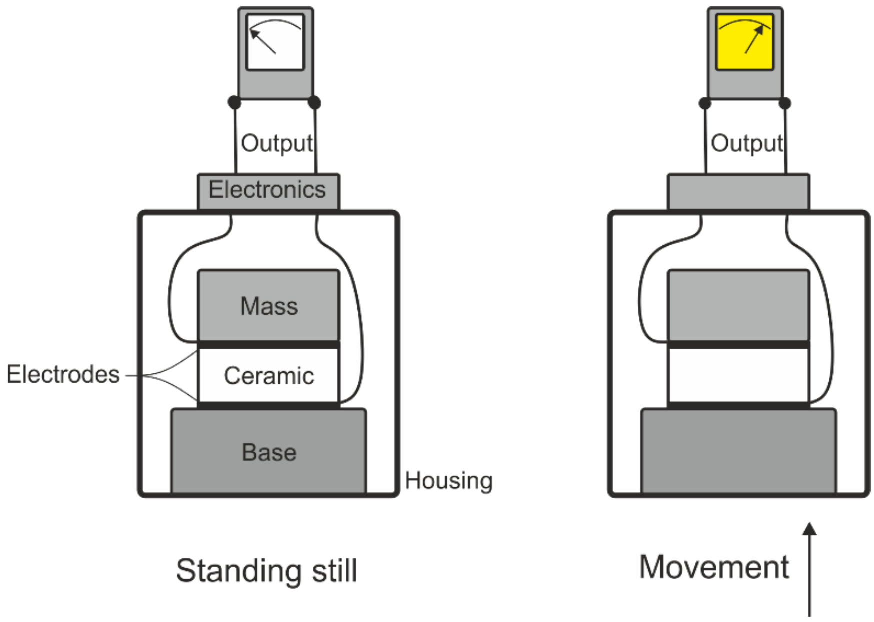


Figure 14 Schematic of a piezoelectric accelerometer. Left, accelerometer is in equilibrium (no motion). Right, the sensor housing is accelerating upwards. The ceramic element is subjected to pressure displacing the atoms in the crystal lattice structure creating a potential difference between the ends.

Capacitive, piezoresistive and piezoelectric accelerometers are based on the same basic principle that there is a proof mass moving when force is applied on it. The difference between the systems is how the force is measured, e.g., change in resistance or capacitance.

As they are vector sensors, accelerometers are directional, which must be taken into account during deployment. Usually, three accelerometers are aligned in three mutually perpendicular orientations to represent sound in three-dimensional space via a coordinate system. Observe that accelerometers can be bought with one-, two- or three-dimensional measuring capability.

Many accelerometers have a small physical size giving a possibility to mount sensors in a small package that will form the sensing head of the system (e.g., a waterproof body). The downside with most accelerometers at the time of writing is the relatively high self-noise amplitude limiting their use to high sound amplitude measurements. The relatively high noise amplitude stems from the small physical size of the sensing component.

More details on examples of accelerometer-based PM systems, both commercial and custom built, and experiments can be found e.g., in (Ceraulo et al., 2016; Dall'Osto, 2016; Kim et al., 2004; Sigray et al., 2011).

7.2.2 Pressure gradient hydrophone arrays

Hydrophone arrays present an indirect way of measuring PM (the limitations and calculations for this are described in Section 5.3). Classically, hydrophone arrays have been used to estimate the PM by measuring pressure gradients. The hydrophones are arranged in different configurations for evaluation of the motion. At least four hydrophones are needed in a pyramidal geometry in order to capture the PM in three dimensions. The inter-hydrophone distance error can have a large impact on the PM-estimation measurement errors (Section 5.3 of this guide and Gray et al., 2016). Also, when the wavelength of the impinging sound is shorter than half the distance between the hydrophone elements there will be ambiguity about the direction of the sound source. To have better control of the inter-hydrophone distance, segmented hydrophone elements can be used inside a moulded casing.

If using hydrophones in a configuration that does not span over three spatial dimensions one should be aware of that wave motions in the "missing" dimension will not be recorded. Also, using hydrophones near a pressure release boundary (close to the surface or other volumes with air/gas/vacuum) will not yield reliable results since the sound pressure drops at the boundary, see Section 6.3.

7.2.3 Sensors that measure particle velocity

Geophones

Geophones consist of a mass with a coil attached to the housing with springs and are used in the marine environment (Bastyr et al., 1999), see Figure 15. Inside the mass/coil system is space for a magnet that is attached to the housing. As the housing with magnet vibrates relative to the mass/coil system, the motional magnetic field induces measurable currents in the coil. Geophones are highly sensitive with low self-noise, making them suitable for low-amplitude measurements. These characteristics come from the large dimension of the spring-mass system (moving coil). The self-noise (thermal) amplitudes are typically lower than in accelerometers. The frequency band of geophones is usually from a few hertz up to hundreds of hertz (Chapter 6). As they are vector sensors, geophones are directional, which must be taken into account during deployment.

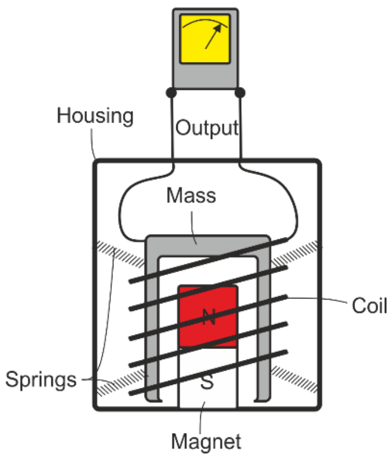


Figure 15 Schematic of a geophone.As the housing with the magnet moves relative to the mass/coil system currents are induced in the coil. The mass and coil are attached with springs to the housing.

Temperature variation

The Hydroflown™ (Microflown Technologies BV Inc) sensor measures heat variations in thin platinum wires as sound waves impinge the sensing head (de Bree et al., 2004). Preliminary data show that the sensor is usable in the frequency range of 5 Hz to 1 kHz with low self-noise characteristics. There is no commercial underwater sensor of this type yet. The size and suspension requirements of the instrument may make it simple to use. It is roughly the size of a hydrophone, and the calibration of this sensing device does not depend on its buoyancy, however motion of this sensor should be avoided, because it measures the flow relative to the sensing wires. Therefore, the suspension may be critical.

7.2.4 Sensors that measure particle displacement

As of July 2020, there are no commercial sensors that measure particle displacement. Experimental particle displacement sensors have been tested using eddy current measurements (Donskoy, 2011) and tested displacement measurements on neutrally buoyant magnetic bodies (Linné and Sigray, 2019).

7.3 Accelerometer-based instrument specifications to consider

The most important sensor specifications to consider are listed below. The exemplified specifications are typical for accelerometers, in some places additional information relevant to geophones is given. The recommended sensor specifications stem from the fact that commercial PM sensors are based on accelerometers.

Sensitivity

The total sensitivity of the instrument depends not only on the sensor sensitivity, but also on the buoyancy of the PM sensor and how the sensor has been attached to it. Sensitivity shifts will appear depending on how heavy/light the head is in the water according to the formula (Leslie et al., 1956, McConnel, 2003):

$$\frac{u_{\mathrm{s}}}{u_{\mathrm{w}}} = \frac{3\rho_{\mathrm{w}}}{2\rho_{\mathrm{s}} + \rho_{\mathrm{w}}}, \qquad \text{Equation 47}$$

where

u_{s} = the velocity amplitude of the sphere;
u_{w} = the velocity amplitude of the medium (water);
ρ_{w} = the density of the medium; and
ρ_{s} = the density of the sphere.

The sensitivity shift will scale acceleration equally.

Calibration

Accelerometers are accompanied by a manufacturer's calibration curve of the sensor. The calibrations are usually done using a shaker table where the output has been compared with a reference accelerometer. The manufacturer should provide both a sensitivity and phase response of the accelerometer in the calibration report. If an accelerometer is used as a sensor, then sensitivity given by the manufacturer is normally given in a linear scale, e.g., 100 mV/(m·s^{-2}). The accelerometer specifications normally give the sensitivity error range in percent. For example, if a sensor with the sensitivity of 200 mV/(m·s^{-2}) has been specified to +/-5 %, the sensitivity is then somewhere between 190 mV/ (m·s^{-2}) and 210 mV/(m·s^{-2}).

When embedding an accelerometer in a PM sensing head, the calibration needs to be redone, preferably in water. The reference value for sensitivity of PM sensors is 1 V/(nm·s^{-1}) for particle velocity sensors and 1 V/(µm·s^{-2}) for particle acceleration sensors. See Chapter 8 for further detail on instrument calibration.

Frequency range (resonant frequency/spurious frequency)

The usable frequency band is limited by both the sensor element (accelerometer) and the size of the sensing head. The sensor itself will have a bandwidth where the response is flat. When connected to a body, forming the sensing head or PM sensor, additional mechanical resonances may arise. Non-uniform motion of the sound wave will occur when the sensing head is larger than half a wavelength. The frequency range for accelerometers and thus accelerometer-based vector sensors range is from approximately from one hertz to a few kilohertz. It is important to engineer the PM sensor so that the internal mechanical resonances are outside of the frequency band of interest for measurement.

Accelerometers usually have a resonance peak at relatively high frequencies, e.g., above 20 kHz. When an accelerometer is mounted inside a sensor head new structural resonances will likely appear. Manufacturers usually provide the sensitivity within +/-x % in the frequency interval. The response will show most deviation in the beginning and the end of the frequency band.

The usable frequency for geophones is typically from a few hertz up to few hundred hertz. The band is given by the specified natural frequency (low limit) and spurious frequency of the sensor (high limit), see below. Geophone manufacturers specify the spurious frequency, which is also connected to resonant behaviour in the sensor.

System spectral noise floor (self-noise)

The self-noise of a sensor is a very important parameter since it defines the lowest PM amplitudes one can measure. Table 5 presents examples of self-noise spectral density values that can be found for high end commercial accelerometers available at the time of writing this guide.

Table 5 The self-noise values of high-end accelerometers together the values in dB.

Self-noise	1 Hz	10 Hz	100 Hz	1,000 Hz
square root of system self-noise spectral density / ((µm s^{-2}) Hz$^{-1/2}$)	112	39	12	4.4
system self-noise spectral density level (re 1 (µm s^{-2})^2 Hz^{-1}) / dB	41	32	22	13

Orientation of sensor

Earth's magnetic field: A compass or magnetometer is a valuable feature if one is interested in connecting the direction of the PM with the Earth's magnetic field.

Source heading: One can also "calibrate" the orientation using an acoustical source at a known position generating pulses.

Earth gravity: Some acceleration sensors can detect the direction of gravity.

Separation of acoustic centres

As PM sensors are vector sensors, they are capable of determining the direction to a sound source with 180° ambiguity (using accelerometer output only). Beamforming calculations can be used to produce lobed plots that indicate sound directionality and PM sensor (accelerometer only) data can be used to produce bi-polar shaped lobes (think of number 8) on the plot. The "true" lobe is accompanied with a lobe that is 180° offset. If the user has no other information about the position to the source it is not possible to determine which lobe indicates the true direction. However, if a PM sensor also has a hydrophone, calculating the intensity using the sound pressure and PM leads to the "false" lobe being suppressed yielding the direction to the source. For optimal performance, the acoustic centre of the hydrophone and the PM sensor should be the same. The acoustic centre is defined as the point from which acoustic waves seem to emanate when the transducer is used as a source (Jacobsen et al., 2004). The acoustic centre in underwater transducers is usually defined by the manufacturer in the specified frequency range. The acoustic centre is the same when a transducer is used as a sound source or receiver.

If the acoustic centres of the accelerometer and the hydrophone are separated, there will be frequency dependent ambiguity to the direction to the source. Beamforming calculations will generate grating lobes when half of the wavelength is the same, or shorter, as the separation distance of the acoustic centres. The grating lobes can be mistaken for the direction to the source.

For example, if the separation of the acoustic centres of the hydrophone and PM sensor is 20 cm, side lobes will start to appear at a frequency with a wavelength corresponding to approximately the speed of sound divided by two times the separation:

$$f = \frac{c}{\lambda} \approx \frac{c}{2h} \approx \frac{1500\ \text{m/s}}{0.4\ \text{m}} = 3750\ \text{Hz}\,, \qquad \text{Equation 48}$$

where

c is the speed of sound in water; and
λ is the wavelength.

Above this frequency there will be ambiguity in the direction to the source.

It is also important to be aware of that if making intensity measurements using separated acoustic centres between the hydrophone and PM sensor, the phase difference between signals has to be considered.

Buoyancy

A neutrally buoyant sensor minimally changes the field that is being measured but as a practical matter, a negatively buoyant sensor can be easier to deploy. If properly constructed and calibrated, there should be no adverse effects from a heavy sensor used in isolation. A heavy sensor will alter the acoustic field in the region of one-two sensor diameters, creating a wake region that could interact with nearby sensors or reflective boundaries. Also, see subsection "Sensitivity" above together with Equation 47 on how the sensitivity of the sensor is affected by the density of the sensor.

7.4 Other sensor specifications

A few other typical accelerometer characteristics are explained.

Phase response

This is the phase difference between the actual wave and the signal from the sensor.

Non-linearity

The deviation of the sensor output curve from a specified straight line over a desired acceleration. Non-linearity causes distortion and can generate apparent energy at frequencies where there is none.

Transverse sensitivity

Transverse sensitivity is the sensitivity of the accelerometer at 90° to the sensitive axis of the sensor. This is due to sensor alignment error for the three "orthogonal" directions. The error to one axis (εV_1) becomes:

$$\epsilon V_1 = \sqrt{(d_2 V_2)^2 + (d_3 V_3)^2} \qquad \text{Equation 49}$$

where V_2 and V_3 are signal output values from the two perpendicular axis and d_2 and d_3 are the alignment error values in percent. They can be neglected when the total acceleration is measured.

7.5 Signal conditioning

Prior to digitisation, it is necessary to improve the SNR of the signal. The signal condition unit consists of the following components listed next.

Amplifier

The role of an amplifier is to increase the amplitude of signals. The amplifier settings are normally user selectable in both data logger- and cabled systems.

Input range

Sometimes manufacturers of data acquisition systems may have defined an input range. This may be found in computer-based data acquisition systems with oscilloscope settings. This means there is an amplifier in the system. Changing the input range is the equivalent to setting an amplifier gain, the difference being that the computer system rescales the signal automatically. If one has a maximum ±5 V input range in the system and the user sets the input range to ±0.5 V. The system amplifies the signal by a factor of ten and rescales it accordingly.

Filter

A filter limits signal levels at certain frequencies depending on filter type. One very important form of filter is an anti-aliasing filter, which removes low frequency artefacts from signals having higher frequency than half the sampling frequency, also known as the Nyquist frequency. The filter must be implemented before digitisation, otherwise the data are more or less useless. Many manufacturers have an automatic anti-aliasing filter setting in the system that the user cannot modify. Since the filters are not ideal the usable bandwidth of the recording is up to approximately 40% of the sampling frequency, e.g., if one samples data at 20 kHz the upper usable limit is 8 kHz. Many systems also have a high pass filter with a few user selectable settings, see also Section 5.3.1.

In general, appropriate application of filters improves the SNR.

7.6 Analog to Digital Converter

After the signal goes through the signal conditioner, it is digitised for analysis and storage. Analogue-digital converters (ADCs) come with many specifications listed in the following.

Dynamic Range

The measuring system's effective amplitude range, see Section 5.3.2.

Resolution

Determines the resolution of the measured signals. Most acquisition systems have 16- or 24-bit depth. The number of evenly distributed levels becomes 2^{16} = 65 536 and 2^{24} = 16 777 216. If one has a ±5 V measurement range the system can detect changes of 10/(65 536) V = 153 µV with the 16-bit system and 10/(16 777 216) V = 0.59 µV with the 24-bit system. The resolution should be compatible with the SNR capabilities of the sensor.

Sampling frequency

The sampling rate of the system should be more than twice the maximum acoustic frequency of the signal. To avoid aliasing, a low pass filter must be applied at 50 % of the sampling frequency. The 50 % mark is not ideal because it allows a frequency band that contains only partially attenuated signals above half the sampling frequency, for which aliasing can result. A conservative recommendation to achieve an alias free measurement is to apply a 40 % low pass filter of the total measurement bandwidth. The sampling frequency should also be matched with the sensor type. If the maximum stated measurement frequency of the PM sensor is 2 kHz there is no need to sample data at 100 kHz frequency but instead a minimum of 5 kHz. A better sampling rate is 10 to 20 kHz as that provides five to ten samples per oscillation at the highest sensor frequency (2 kHz). This should be optimized with the data storage size. See also frequency response and sampling frequency in Section 5.3.2.

7.7 Microcomputer/computer

System clock

An important specification to look for is the system clock and its drift. All clocks drift, but with computers connected to the internet this is rarely a problem since the computer clock can be recalibrated using an internet time server. However, for autonomous recording systems the clock drift is an important variable (see Section 4.3). When high precision is needed, a GPS clock can be attached to the computer. Autonomous data loggers have a small programmable microcomputer through which the user can control various settings of the logger, e.g., set sampling rate, logging periods etc. These devices also have a quartz clock that keeps track of time. The problem with these clocks is that these cannot be synchronised while these are deployed in the sea. A quartz clock having a 20 parts per million drift is quite common. This gives a possible total drift of 1.7 seconds per day.

For long-term measurement a chip scale atomic clock is an excellent but pricey alternative. Depending on type, the drift can be a few microseconds per day. For time critical measurements involving phase of signals, the chip scale atomic clock is essential.

7.8 Data storage

Autonomous data loggers store data onto an SD card or a flash memory, for which there is a limit to the space available. For long-term measurements the sampling frequency of the system will determine the amount of data that can be collected. If one uses a 24-bit system with a continuous 10 kHz sampling rate the system will capture at least 30 kB/s (24 bit·10 kHz =3 B·10 kHz=30 kB/s) or approximately 2.6 GB per 24 hours. The required amount of storage is also determined by the type of data format the system uses.

With cabled systems, the user can use the computer's hard disk to store data. Solid state drives, being more robust, are recommended.

7.9 Checklist

Requirements

- Select appropriate PM sensor type and measurement system for the type of measurement being conducted.
- Match the sound level and frequency range of the planned measurement appropriately with the sensor type and system, accounting for frequency response, directivity, dynamic range, and self-noise.
- Consult an expert in underwater acoustics and PM sensors for advice on appropriate instrumentation.
- Use at least a 16-bit acquisition system

Recommendations

- System clock drift is an issue for autonomous data loggers, account for time synchronization of system clocks using GPS or atomic clocks (Section 7.7).
- Use a 24-bit acquisition system to reduce the risk of clipping.

8 Calibration

8.1 Introduction

Calibration of PM sensors is a field where international standards still are under development. In order for any measurement to be meaningful, a sensor must be calibrated by comparing its measurement values to agreed standards. Ideally, these standards would be provided by national metrology institutes, which are validated by international comparisons exercises undertaken under the auspices of the International Bureau of Weights and Measures (BIPM). The methods used for the calibrations should be those described in published international specification standards, such as those produced by the ISO or the IEC. Currently, there are no published international specification standards for the calibration of PM sensors in water. Additionally, no national metrology institutes or accredited calibration laboratories offer calibration of sound PM sensors as a routine service. However, several researchers have published scientific papers describing methods for such calibrations and a new standard is in development to address this need (IEC 63305 in IEC TC87). In this section, we aim to describe calibration methods in sufficient detail for readers to know what to expect from a 'best practice' calibration.

The calibration methods discussed in this chapter may be applied to sensors responding to the sound particle velocity (geophones), acceleration (accelerometers), or to hydrophone arrays which respond to pressure gradients (sometimes used as a proxy to derive sound PM where the acoustic field conditions are known – see Section 4.3). Such sensors are generally referred to as PM sensors or "vector sensors" that possess three channels, one channel for each of the three orthogonal components of the acoustic field. The calibration methods described fall into several categories:

- free-field methods implemented for frequencies from about 500 Hz to tens of kilohertz where the sensor is exposed to a plane or spherical travelling wave generated by a source transducer; in laboratory water tanks or open-water conditions;
- calibration in tubes where the excitation is generated as a travelling wave or standing wave;
- in-air calibration check using a shaker.

Published methods include the extension of free-field techniques based on the reciprocity principle (Isaev et al., 2014; Chen et al., 2019; Guanghui et al., 2019), and based on optical techniques (Theobald et al., 2007). Methods have also been reported for lower frequencies of between a few hertz and 1 kHz based on calibration tubes and oscillating columns (Bauer et al., 1972; Strasberg and Schloss 1973; Ivanov et al., 1981; Gordieski et al., 1994). Two metrology institutes have even reported a successful calibration comparison for both free-field and calibration tube-based techniques (Isaev et al., 2019). We do not expect all readers to be able to perform calibrations themselves after reading this chapter, but the requirements and recommendations for 'best practice' will be highlighted to give readers the basis for informed discussions with those performing calibrations.

The calibration of a PM sensor requires that the response of the sensor be determined when it is exposed to a known sound field. Just as with hydrophones, the required sensitivity of the sensor is the response to exposure of an acoustic plane-wave. During free-field calibration, plane-wave sources are difficult to generate with spherical sources more commonly used, and the typical propagation distances are relatively short such that the acoustic field is spherically spreading. In such configurations, a plane-wave approximation cannot always be assumed. In this case the correction described in Section 4.1 (Table 3) is required unless the $1/r$ component of the pressure gradient is far less than the plane-wave component of pressure gradient (see Section 4.1).

8.2 General procedures for calibrations

8.2.1 Type of calibration

Two general types of calibration may be defined:

Absolute calibration without the need for an acoustic reference transducer

Such methods include free-field reciprocity calibration, standing wave tube calibration using an accelerometer, and optical interferometry. Free-field reciprocity calibration is based upon the principle of acoustic reciprocity, with the method requiring three acoustic transducers, at least one of which must be a reciprocal transducer. The application of the reciprocity calibration method to vector sensors is described in a number of published papers (Isaev et al., 2014; Chen et al., 2019; Guanghui et al., 2019). Standing wave tube calibration is based on the measurement of a physical parameter, such as oscillating velocity or acceleration. In the case of the optical method, a laser interferometer is used to directly measure the sound particle velocity. Note that in these cases, an additional calibrated instrument is needed (for example, an accelerometer or laser interferometer).

Relative calibration using a calibrated acoustic reference transducer

Calibration is performed by comparison to another acoustic hydrophone which has already been calibrated by absolute methods. The accuracy of a comparison calibration is degraded compared to an absolute calibration, mainly due to the added uncertainty contributed by the acoustic reference device.

8.2.2 Acoustic field requirements

For free-field calibrations to be valid, the following general requirements must be satisfied (IEC 60565-1: 2020):

- Acoustic free-field conditions require minimal influence from acoustic reflections from medium boundaries (see 6.2.1 of IEC 60565-1:2020);
- Acoustic far-field conditions require sufficient separation distance between projector and sensor (see 6.2.2 and 6.2.3 of IEC 60565-1:2020);
- Acoustic plane-wave conditions require a correction to be made when spherical acoustic field conditions are used (see Table 2 for details of correction); and
- Acoustic steady-state conditions require attenuation of any transient behaviour displayed by resonant transducers (see 6.2.4 of IEC 60565-1:2020).

For valid standing wave tube calibrations, the following general requirements must be satisfied:

- A standing wave is produced in the calibration chamber (see 6.3.1 of IEC 60565-2:2019); and
- The wall of the calibration chamber is rigid relative to media (water) inside the chamber (see 6.3.2 of IEC 60565-2:2019).

8.2.3 General measurement requirements

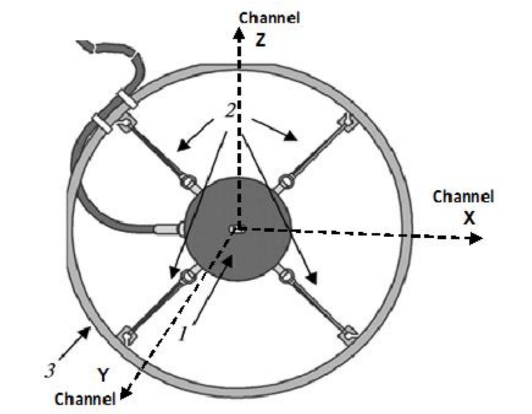
Calibration facility

The free-field calibration tank facility shall enable a minimum of at least two transducers at a time to be positioned reproducibly at a known separation distance and aligned for calibration. Time-limited signals (such as tone bursts) are used with time-gating to eliminate reflections. Such a facility allows convenient access, precise positioning of devices via a rigid support framework or positioning system, and control over the environmental conditions. However, the finite size of a facility places limitations on the frequency range and type of transducer that could be calibrated. For open-water facilities, the deployment of the transducers is typically achieved from the surface using a raft or pontoon.

Suspension of PM sensors

Pressure gradient sensors that do not respond to the PM in the water may be attached to a rigid mount and support. PM sensors that respond directly to PM should be suspended on a calibration bracket (e.g., mounting ring) such that they can move with the water motion freely during the calibration. Usually, elastic materials (such as rubber) are used to suspend the PM sensor ensuring that the sensor maintains the correct position. Also, the measured channel is aligned with the calibration direction. An example of a possible sensor mounting arrangement is shown in Figure 16. The resonant frequency of sensor housing suspended on the elastic material must not be within the frequency range of calibration, and ideally will be well outside it (the resonance frequency may be determined using a shaker table). Care should also be taken to minimise the amount of structure borne noise which may be picked up by the mount and supporting framework and transferred to the sensors.

The choice of mount and supporting framework will influence the PM sensor calibration and must be reported with the calibration results. The suspension and mount should be regarded as part of the sensor, and the same mount should be used for measurements in the field. Some commercially available instruments may encase the mount and calibrate the entire unit before supplying it.



1 – Three-component particle motion sensor
2 – Rubber
3 – Mounting ring

Figure 16 Particle motion sensor suspended on the mounting ring. (adapted from Isaev, 2013 and IEC 63305 WD)

The sensitivity of some PM sensors may vary with both ambient temperature and immersion depth (due to increased hydrostatic pressure). These factors should be stated with the calibration results.

8.3 Calibration methods

8.3.1 Calibration using the spherical-wave reciprocity method

The spherical-wave reciprocity method is an established absolute free-field method for calibration of hydrophone and source transducer in the frequency range of 500 Hz to 500 kHz; details described in IEC 60565-1:2020. The method may be adapted for calibration of the pressure gradient sensitivity of a PM sensor (Isaev, 2014; Chen, 2019). Three transducers are required, one of which is the PM sensor being calibrated. The sensitivity of the devices can be determined from the *purely electrical* measurements, the measurement of the separation distances, and the knowledge of the medium density and acoustic frequency.

8.3.2 Calibration using optical interferometry

The optical interferometry method determines the sound particle velocity in the far-field of an acoustic source transducer. The optical interferometer measures the motion of an optically reflective and acoustically transparent membrane suspended in the acoustic field (the membrane thickness is much less than the acoustic wavelength, with typical thicknesses of 40 μm). The PM sensor is then positioned with its reference centre at the same point in the acoustic field that has been interrogated by the optical beam, and the received voltage is measured. The free-field sensitivity is then calculated from the quotient of the received voltage and the particle velocity or acceleration (Theobald et al., 2005). The optical interferometer is typically a heterodyne interferometer (or "vibrometer") which uses the frequency shift of the laser light to determine the velocity of the pellicle.

8.3.3 Relative free-field calibration

The calibration of a PM sensor in free-field conditions may be undertaken by a comparison method. The reference device may be either another PM sensor, or a reference hydrophone (for a calibration of the pressure gradient sensitivity). The basic principle of the methods is that the device being calibrated and the reference device are exposed to the same acoustic field (generated by an auxiliary projector which need not be calibrated), and then the sensitivity of the sensor being calibrated is calculated from the product of the reference device sensitivity and the ratio of the received voltages of the two devices. Such a comparison calibration is less accurate than a primary absolute method because of the uncertainty introduced by the reference device.

8.3.4 Calibration using standing wave tubes

The standing wave tube calibration method uses a column of water open at the top and excited by a transducer in the base. The tube must be constructed with rigid walls (typically made of aluminium or steel). A calibrated accelerometer measures the acceleration at the base due to the driving excitation. The method can be applied for the frequency range of 5 Hz to around 400 Hz. The column filled with water is excited externally by a sinusoidally driven transducer (or vibration generator). On the surface of the water, the sound pressure is equal to zero, and a standing wave is generated in the chamber. The vector receiver is positioned at a known depth in the water and the accelerometer is fixed on the bottom of the chamber (Bauer et al., 1972; Strasberg and Schloss 1973; Ivanov et al., 1981; Gordieski et al., 1994).

8.3.5 Calibration using a shaker in air

The sensitivity to acceleration may also be measured in air using a shaker or vibrator to generate the motion, with the motion determined using a calibrated reference accelerometer or laser interferometer. Using the shaker in air method has been standardised for calibration of accelerometers using optical interferometers [ISO 16063-11:1999]. A weakness of this method is that the sensor is not immersed in water and is not mounted in the mount that is used when employed in the field. However, a correction can be made for buoyancy using the formula of Leslie given in equation 46 (Leslie, 1956). This is a very quick method which may be used as a check before going on a sea-trial or during post trial checks.

8.3.6 Phase calibration

In general, the sensor and measuring system may introduce a phase delay into the measured signal. This may be accounted for by representing the sensitivity as a complex valued quantity, the modulus of which represents the magnitude-only response, and the phase of which describes the phase response of the system. The phase information in the signal can be distorted by a severely non-uniform frequency response in a sensor. For calculation of acoustic metrics which depend on the energy or power in the signal, this is not a problem. However, a non-uniform phase response may have a significant effect on time-domain metrics such as peak sound particle acceleration or velocity. Typically, the phase response of the sensor (and measuring system) is not known. For cases where the phase response is known and where the response varies significantly with frequency in the frequency range of interest, a deconvolution approach can be used to re-construct the time-waveform. Further guidance is given in [ISO 18406:2017].

8.4 Reporting of calibration results

The PM sensor sensitivity results shall be reported for each measurement acoustic frequency. The results for pressure gradient sensitivity, particle oscillation velocity sensitivity, and particle oscillation acceleration sensitivity of a vector receiver shall be reported separately in units of volt metre per pascal (V m/Pa), volt second per metre (V s/m) and volt second squared per metre (V s^2/m). If the PM sensor contains a hydrophone and the sensitivity can be expressed as a sound pressure sensitivity, the unit of sound pressure sensitivity is volt per pascal (V/Pa).

The calibration uncertainty shall be reported alongside the sensitivity, with the uncertainty evaluated in conformance with the ISO Guide to the Expression of Uncertainty in Measurement [ISO/IEC Guide 98-3:2008]. It is recommended that the calibration uncertainty be expressed as a relative uncertainty in percent.

When the calibration results for a hydrophone or accelerometer are reported, the environmental conditions that pertained to that calibration shall be stated, including all conditions that may influence the sensitivity of the device. Conditions that should be reported include: date of the calibration; water temperature; sensor immersion depth; type and description of sensor mount and supporting framework; length of soaking time and wetting procedure used; orientation of the transducer including axis or alignment mark; alignment method (manually or acoustically aligned); any assumptions made about the device under test (e.g., the position of the reference centre).

8.5 Checklist

Requirements

- Calibrate the sound PM sensor over the frequency range of interest (Section 8.1).
- Include the phase response with the calibration (Section 8.3.6).
- Provide an uncertainty with the calibration (Section 8.4).
- State the sensitivity in S.I. units (Section 8.4).
- Report the suspension method used for the sensor calibration and as far as possible use the same method in the field measurements (Section 8.4).

Recommendations

- The calibration certificate should also state: date of the calibration; water temperature; depth of immersion; orientation of the sensor (Section 8.4).
- Where possible, the calibration should be traceable to recognised standards (Section 8.1).

9 Particle Motion Measurements in Open Water and Tanks

9.1 Introduction

As outlined in Chapters 0 and 4, PM should be reported when it is of biological importance. When PM is reported, PM should be measured rather than calculated from pressure as appropriate to the acoustic conditions (Chapter 4). When PM is measured, it should be measured in three orthogonal axes (x, y, z, with z pointing down). Measurement of PM can be carried out under two general experimental conditions, in an 'open water' environment and in a laboratory tank. We use the term open water to mean both offshore and inshore environments as well as enclosed outdoor environments such as rivers, lakes, and reservoirs. The ecological and acoustical relevance to real world scenarios is generally higher in open water, if it is representative of the home range of the species of interest and the propagation properties of the water in which it lives. It is also quite often the only feasible approach to measure large acoustic sources. However, open-water experiments are inevitably less controlled than tank environments. Experiments designed to examine specific research issues can benefit from the controlled environments provided by test tanks, for example many physiological tests. It may also be desirable to know the soundscape of tanks that are used for other purposes such as public aquaria, housing for species used in aquaculture, biomedical research and so on.

Calculating PM from single hydrophone measurements may be done when a plane wave is a suitable approximation (the conditions for which are outlined in Chapter 4), but for the shallow water habitats and low frequencies used by many PM sensing animals, the assumptions of plane wave or spherical spreading from a monopole approximations are not met and direct measurements are required using PM sensors. Provided the conditions outlined in Chapter 4 are met for the validity of the pressure gradient method, hydrophone arrays can be considered as PM sensors for the purpose of this section. In this chapter we provide basic general instructions for how to make measurements with PM sensors. These guidelines apply to biological applications (this means the received PM at the location of a biological receiver) this applies to soundscapes, anthropogenic noise, and fish hearing.

9.2 General requirements

9.2.1 Environmental conditions

Some of the advantages of open water measurements compared with tank measurements include the potentially very large variety of in-situ locations available, the authenticity of using a realistic environment for the study, the reduced number of boundaries which complicate the sound field and the possibility for long-term monitoring of the real aquatic environment. However, measurements in open water can be affected by variable environmental conditions, higher background noise and greater deployment challenges such as the positions of sensors and source, so some special considerations need to be taken in order to make reliable measurements that result in usable data.

Measurements in tanks are perhaps more convenient; it is easy to deploy sensors in stable environments at much lower cost. The main disadvantage in comparison with open water is the low frequency limit where free-field conditions can be achieved depending on the size of the tank, so that measurements at low frequencies are likely to be made in a reverberant environment of a tank where sound pressure and particle velocity fields are complicated, much more difficult to control and can change dramatically over short distances (Parvulescu, 1967; Rogers, 2016; Gray et al, 2016). The size of the PM sensor in relation to the tank may mean that the sensor is unable to measure PM with enough spatial resolution For example, many fish hearing tests are conducted just below the surface of the water but some PM sensors may be > 20 cm in height, the change in sound level over 20 cm of depth of water from the surface in a small tank is likely to be very great, making any measurement unrepresentative of the PM close to the surface. The effect of the tank on the measurements is different for PM from what it is when pressure is measured, to quantify the difference it is recommended to report the impedance (ratio of PM to pressure) compared with the impedance expected in a free field (Vetter et al., 2019).

It is important to know in what environment a measurement will be taken. Setup and deployment of instrumentation depends on the environment, and the measured PM will be different at the same sound pressure under different environmental conditions (temperature, salinity) due to differences in acoustic impedance of water. The temperature profile of the water should be measured if the propagation of the sound (e.g., for determination of acoustic source level) is of interest. Water salinity can vary from fresh to brackish or salty water. Salinity will influence the sensors buoyancy, which in turn can have an impact on the results, since the acoustic impedance relates sound pressure to particle acceleration, see Section 7.2 and Gray et al. (2016). One can use Equation 47, (Leslie et al., 1956), to check how density change due to salinity will affect the measurement and rescale the instrument's sensitivity accordingly (if calibration has been performed in water with different salinity). The calibration of the sensor must be appropriate for the conditions in which the sensor is used (see Chapter 8).

The bottom properties such as sound speed and density as well as wind speed are useful information for an open water measurement if it is carried out under non free-field conditions.

Background noise can reduce the quality of measurement. It is necessary to choose a venue away from any known noise source in open water.

9.2.2 Acoustic sources

Acoustic sources in open water are often not under the control of those making the measurements. Examples of anthropogenic acoustic sources include marine pile driving, detonation of un-exploded ordnance, geophysical surveying, or marine traffic. Exceptions to these might be exposure experiments on marine fauna, for example where playback experiments are undertaken. However, for tank experiments the acoustic source is most often under the direct control of the user. This has the advantage that the output is controllable so that the acoustic field can be adjusted according to requirements of experiment. Pulsed or burst signals can also be used with a common trigger used for data acquisition, allowing the use of time-gating techniques to isolate the direct signals from tank boundary reflections to simulate a free-field environment. If the source is in the water volume, this is not an option for low frequencies with small tanks with limited echo-free time (IEC 60565-1:2020). Note that the whole tank can in some applications be shaken.

9.2.3 Position within tank

In many bioacoustic studies, the water depth or sizes of tanks are smaller than the smallest wavelength (Rogers et al., 2016). The walls and the bottom of the tanks can be glass or other thin materials, including steel. They are transparent to the acoustic wave at the frequency of interest and behave as a pressure release boundary. The particle velocity increases very quickly while sound pressure decreases near the boundaries. When possible, placing the source and receiver away from the boundaries of the tank avoids potentially large errors in measured data with a small position uncertainty. The acoustic modes within the tank coupled with the possible flexural mode of the walls and bottom should be examined to assess the effects on the signal, for example to scan the signal within the frequency range for any resonant peak.

9.3 Measurement steps

At the time of writing, there are several different sensor types that can be used to measure PM, see Chapter 7 Instrumentation, each with its own unique suspension and buoyancy adjustment method, unlike hydrophones. Therefore, the below section gives a general overview of what to consider when performing PM measurement, without providing examples for a specific sensor type. This section is limited to measurement in the water column and not on the seafloor which is described in Chapter 5.

9.3.1 Preparation (Power up system, program and check signals)

Connect all instruments and power the system if you have a cabled system or program the autonomous system if such is being used. Take detailed notes on system settings, sensor specifications and data acquisition method. It is recommended that users standardise their own protocol. Depending on the situation, a test measurement is recommended before the actual measurement start in order to test the system and record some background noise to check the level.

With a controlled source, select signal type accordingly for the measurement and plan for measurements using signals repeatedly. Signal averaging improves SNR with pulsed signals.

9.3.2 Deployment of the sensors

Measurement setup and rig design differ between tank and the open water scenarios but are equally important. The setup and rig design includes the suspension of the PM sensor, mounting options and adaptation to the environment to minimise flow noise and rig related disturbances.

Rig design

The design of the system that keeps the PM sensor in the planned position in the water column can look very different and depends on the sensor design (autonomous or cabled) and measurement conditions. The rig can be bottom mounted, suspended in the water column from the bottom, or suspended in the water column from the surface (Figure 17). If the rig is bottom mounted, care shall be taken to avoid sediment vibrations, if the rig is suspended in the water column from the surface it shall be de-coupled from the surface motions. In a tank, a PM sensor can be suspended at the chosen depth from a carriage above the tank but shall be isolated from vibrations of the tank walls (Figure 9). It is important to test the rig configuration beforehand to avoid unwanted disturbances (for example cable rubbing noises).

Before putting the source and receivers into water, wet the surfaces of the source and sensors thoroughly with a surfactant to prevent air bubbles from attaching to the surfaces. Air bubbles can strongly affect sound pressure measurements and, to a lesser extent, accelerometer measurements. The source and sensors should then be soaked in the water well before measurement to eliminate possible performance drift due to temperature change in the devices. The sensor’s position should be recorded as accurately as possible. In open water with deployment from the surface, a GPS device can be used. In open water with deployment without a surface buoy (e.g., in deep sea areas) acoustic navigation systems such as ultra-short baseline systems can be used. In tanks the proximity of the sensor to tank walls, bottom and surface should be recorded. Meta data on sensor position should be noted in the protocol. The measurement geometry that is the distance and angle between the PM sensor and the source, bottom, surface, and any sides should also be noted in the protocol.

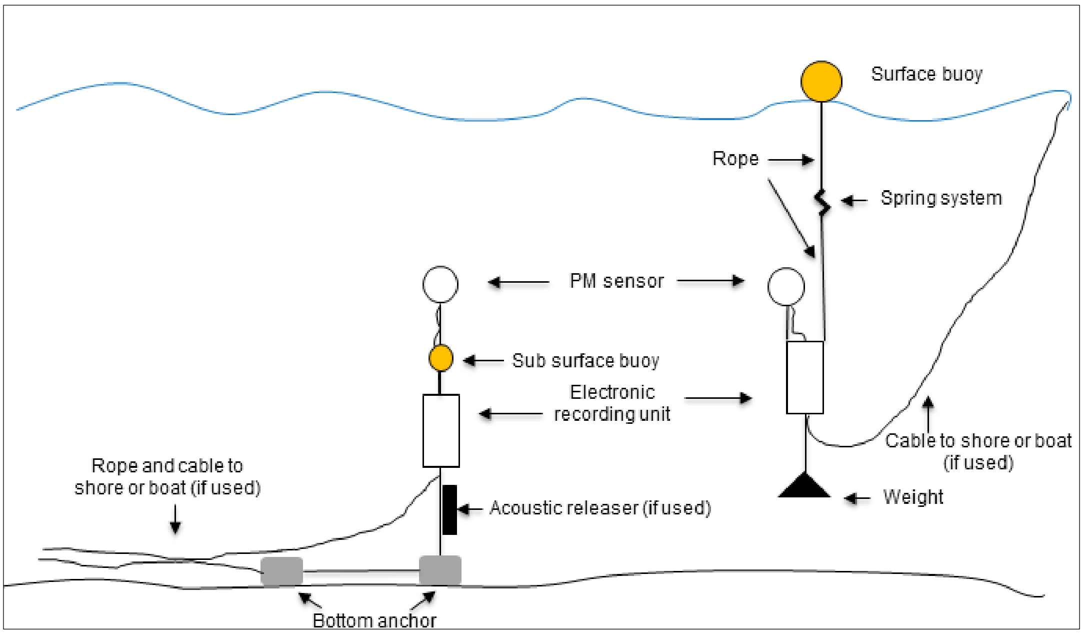


Figure 17 Examples of suspensions of a PM sensor. In order to minimise flow noise, wave motions and sediment vibrations. Note that a PM sensor can be suspended in many more ways and one can use acoustic releasers, ropes, and buoys in different ways.

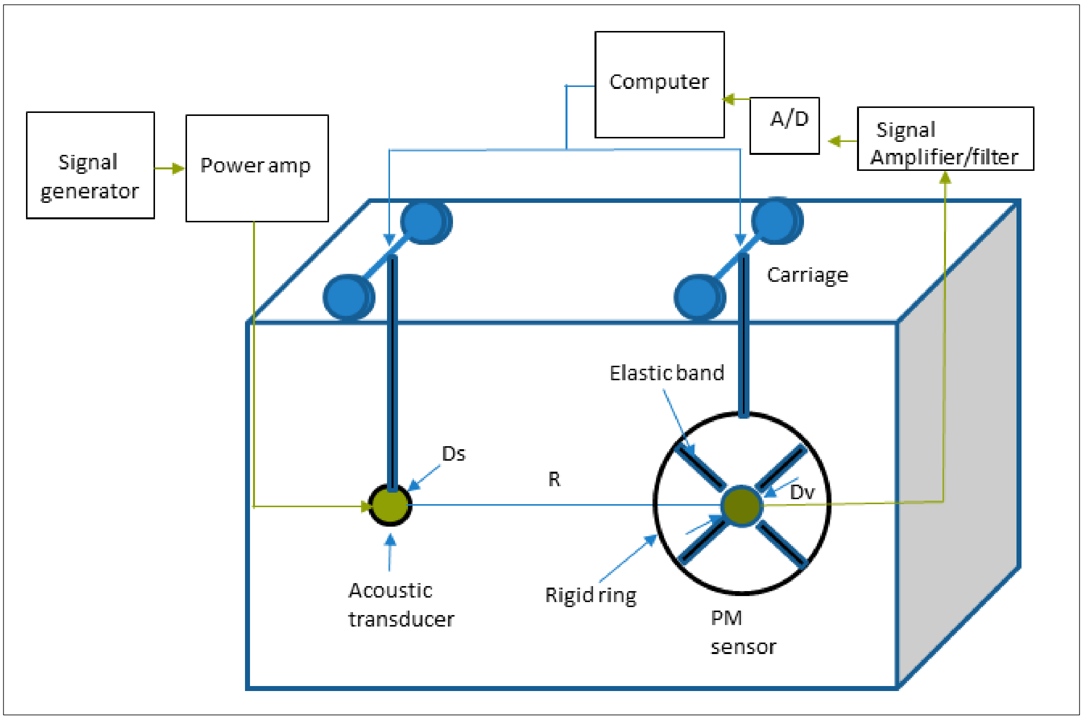


Figure 18 Example of an experiment setup to measure particle motion in water tank. A transducer of diameter Ds is driven by power amplifier with a given signal from the signal generator. PM is measured with a sensor of diameter of Dv, which is suspended with elastic bands attached to a rigid ring. Received signal from the PM sensor is amplified and filtered before converting to digital output by the ADC. Carriage is used to position and align the source and sensor. Decouple the carriage from the walls of the test tank to reduce the influence of vibration.

Sensor suspension

The calibration of a sensor is specific to the method of suspension of the sensor (which also accounts for its buoyancy) because the compliance of the suspension can influence the motion of the sensor. Therefore, always suspend the accelerometer according to the recommendations of the manufacturer and in consultation with the party responsible for calibrating the sensor. Flow noise is typically mitigated in two ways: physical separation of the sensor from the flow (suspend the sensor away from things that move freely, add barriers, scuff coats, blankets), and spatial integration (enclosure in a larger vessel so the net force from turbulence is suppressed, and/or use of multiple sensors). Care needs to be taken since spatial integration can affect the measurement frequency range.

Sensor alignment

Deployment of a sensor that measures PM needs more planning than a hydrophone simply because PM sensors are directional while a hydrophone tends to be omnidirectional. Alignment is sometimes difficult in offshore deployments, but it is recommended to measure and correct for this over time. It is possible to align a PM sensor with a compass, or by fixing on the direction of a known sound source. With a sensor that can move in the water column it is important to make ongoing alignment measurements. In order to receive maximum signal in one axis (useful if SNR is low), one of the axes of orientation of the PM sensor should be chosen in line with the direction of acoustic propagation. Visual alignment aided with acoustic alignment could be applied in this process. Acoustic alignment is achieved by moving the PM sensor translationally in a plane normal to the incident wave and rotationally in order to maximise the received signal. Or having a controlled source moving around the sensor at a certain distance. This is not necessary if the sensor's directional response is available, and SNR is adequate in the direction of measurement.

Temporal sampling and spatial effect

The sampling frequency should be at least two and a half times higher than the upper frequency of interest provided that the anti-aliasing (low pass filter) is set at half the sampling frequency. An anti-aliasing filter may be used to remove low frequency artefacts caused by signals of frequency higher frequency than half the sampling frequency, and this may reduce the usable bandwidth. See Section 7.4 for more information on anti-aliasing filtering. The size of the sensor should be much smaller than wavelength (ideally $D < \lambda/10$), where D is the largest dimension of the sensor, λ is the signal wavelength in water. The spatial average effect of a large sensor should be assessed if D is greater than $\lambda/4$.

9.3.3 Measurements of sound pressure and particle motion

In many cases, both sound pressure and sound PM are measured at the same time. We recommend that sound pressure is measured whenever PM is measured. Some sensors are integrated with a hydrophone so that sound pressure can be measured at the same time and position. For PM sensors without a hydrophone, the sound pressure close to the position of the vector sensor with synchronised signal should be measured with a reference hydrophone if it is desired to find the acoustic potential energy in addition to the acoustic kinetic energy resulting from the particle velocity. It is recommended to place hydrophone as close as possible to PM sensor without them interfering with each other. It is possible that sensors placed near one another may interfere with the sound field received by each other, but data on this are lacking. The effect of the distance of separation on the results should be considered, especially at high frequencies (see Section 7.3 separation of acoustic centres).

9.3.4 Sound speed and water density

As mentioned, it can be important to have information on the water density and speed of sound whether in a tank environment or in open water. For example, temperature profiles can affect propagation in the water; sound can be refracted by a thermocline, and the sound of a source at a given distance may vary according to time of day or season. If propagation is of interest, in an open water environment, sound speed and water density profiles in whole water column should be taken before and after a measurement. This can be done with the use of a conductivity, temperature, and depth (CTD) sensor or a sound speed probe (SSP). The CTD measures hydrostatic pressure and not depth, and therefore the hydrostatic pressure should be reported before depth. In extended measurement situations, the profiles should be measured at least twice every day, once in the morning prior to other activities and once at the end of the day. If available, a chain of CTD loggers can be deployed close to the measurement position(s) and record the sound speed continuously.

In a well circulated water tank, a sound speed, temperature, and depth measurement at one point using a CTD, is enough assuming a homogenous condition in the water. There may be a small temperature profile in a very large and deep tank where water is static. Both sound speed and density will be depth-dependent, but the difference may be too small to be considered for most measurements.

9.4 Recommended check lists for measurements

Some procedures are the same whether you measure in open water or in a tank, but many differ, especially procedures linked to a sensor's durability, suspension, and rig design. The below section lists actions that are recommended to perform in either situation to ensure high quality recordings and minimise the risk of damaging the sensor.

9.4.1 Open water measurements

Preparation before deployment (in the lab)

- Have a standardised checklist for preparation to follow. Note all details in a measurement protocol.
- Check sensor system, batteries or power supply, memory capacity and cables.
- The sensor should have been calibrated at least once and tested recently before the measurement. The suspension used in the measurement should also be within the bounds of the calibration.
- Check sensor suspension and alignment, either with a compass, visual or acoustical and adapt to the measurement conditions.
- Clean cable connector and grease it with lubricant. Clean the O-rings contact surfaces and check it for scratches and dirt to avoid sealing problems.
- If using an autonomous logger, program the system, make a copy of the recording schedule and store it for backup reasons.
- Synchronise the clocks of each applied sensor and a control clock (GPS clock). It is recommended to specify the time in Coordinated Universal Time (UTC) on the recording unit. Note time in the protocol.
- Bring necessary equipment such as a CTD or SSP, GPS, spare parts, tools etc.
- Plan for the deployment with ropes, weights and buoys and prepare for adjustments due to changing environmental factors (for example factor changes in tide into rope and cable plans). When choosing your deployment method, take care that no excessive vibrations,

stresses or shocks will be put on the sensor. Think about either surface or bottom mounted depending on sea roughness.

- Prepare the equipment for transport to the measurement site and pack the sensor and other sensitive equipment so it is not damaged.

Deployment

- Check that the environment is suitable for measurements. High waves and strong currents can easily make fieldwork more challenging.
- Prepare equipment for deployment including a system check to test the system has not been damaged during transport.
- Prepare the sensors deployment configuration if this was not done in the lab.
- Check cables, seals, and connectors.
- To avoid air bubbles attaching to the sensor or its mount, wet the sensor by applying very mild surfactant solution with a soft brush before deployment.
- Deploy the sensor at the pre-planned position.
- The sensor's position should be recorded as accurately as possible with a GPS and noted in the protocol.
- The measurement geometry that is the distance and angle or bearing between the PM sensor and any known sources should be noted in the protocol.
- Sound speed and water density profiles in whole water column should be taken before and after a measurement if propagation is of interest.
- Note the seabed type (a sediment core could be taken if seabed is unknown).
- Weather, time of day and tidal conditions should be noted.

After measurement

- Recover the sensor in the most suitable way if an autonomous sensor is used or stop recording if a cabled system is used and recover it. Note time and date in protocol.
- Clean sensors with fresh water and dry.
- Open sensor and secure raw data storage if an autonomous system is used or detach the data storage or secure the raw data in any other way for a cabled system.
- Check the sensor clock for actual time and compare with a GPS. Note any drift (to at least 1s but greater accuracy if the system allows).
- During long time measurements the total drift may be many seconds or even minutes. The drift can be assumed to be linear over time.
- Make a backup of raw data at the first opportunity, possibly on site. Copy the measurement protocol and meta data to the same location as raw data.
- Prepare the sensor for a new measurement or storage.

9.4.2 Tank measurements

Deployment

- Have a standardised checklist for preparation to follow. Note all details in a measurement protocol.
- Check sensor system, batteries or power supply, memory capacity and cables.
- The sensor should have been calibrated at least once and tested recently before the measurement. The suspension used in the measurement should also be within the bounds of the calibration.
- When choosing your deployment method, take care that no excessive vibrations, stresses or shocks will be put on the sensor.
- Check sensor suspension and alignment, either with a compass, visual or acoustical and adapt to the measurement conditions.
- Check cables, seals, and connectors.
- If using an autonomous logger, program the system and make a copy of the recording schedule and store it for backup reasons.
- Synchronise the clocks of each applied sensor and a control clock (GPS clock). It is recommended to specify the time in UTC on the recording unit. Note time in the protocol.
- To avoid air bubbles attaching to the sensor or its mount, wet the sensor by applying very mild surfactant solution with a soft brush before deployment.
- Deploy the sensor at the pre-planned position.
- The measurement geometry that is the distance and angle between the PM sensor and any known sources should be noted in the protocol.

After measurement

- Recover the sensor in the most suitable way if an autonomous sensor is used or stop recording if a cabled system is used and recover it. Note time and date in protocol.
- Clean sensors with fresh water and dry.
- Open sensor and secure raw data storage if an autonomous system is used or detach the data storage or secure the raw data in any other way for the cabled system.
- Check the sensor clock for actual time and compare with a GPS. Note any drift (to at least 1s but greater accuracy if the system allows).
- Make a backup of raw data at the first opportunity, possibly on site. Copy the measurement protocol and meta data to the same location as raw data.
- Prepare the sensor for a new measurement or storage.

9.5 Checklist

Requirements

- Use sensors and instrumentation with the required performance (Section 9.2)
- Ensure sensors and instrumentation are calibrated to traceable standards (Section 9.3)
- Mount the sensors with a suitable suspension framework suitable for the environmental conditions and the rig design (Section 9.4.2)
- Take detailed notes on sensor specification, suspension, measurement geometry (including orientation and polarity) and settings (Section 9.4.2).
- Record all metadata required to describe the experimental context and environment (Sections 9.4, 9.5)

Recommendations

- Measure PM in three orthogonal directions (x, y, z, with z pointing down).
- Make a backup of raw data at the first opportunity, possibly on site. Copy the measurements protocol and meta data to the same location as raw data.

10 Data Processing

Acoustic recordings consist of sampled voltage fluctuations. In order to interpret acoustic recordings an end user may listen to the data, but summary metrics and/or visualisations are required for reporting acoustic data. Data processing and calculations are necessary for producing these summary metrics and visualisations. Projects working on PM shall either adopt an existing data processing protocol or develop their own. The majority of processing of PM data is the same as for sound pressure data, provided the time series is calibrated properly at the start. Therefore, in this chapter we do not repeat detailed material published in other protocols. We provide a flow chart showing the steps in acoustic data processing for some of the commonly used metrics (Figure 19) and signpost the reader to relevant details published in other protocols. Calculations that are unique to PM and are not covered in other protocols include components of vector field quantities (needed to represent the three axes of motion), and intensity (used to determine the direction of the sound source). These are detailed in this chapter. Existing standards for consideration include the JIP Data Processing Standard (Ainslie et al., 2018b) and the ADEON Processing Standard (Heaney et al., 2020). The JIP Data Processing Standard (Ainslie et al., 2018b) provides details for processing time series into multiple metrics for power and energy quantities, their spectral densities, zero-to-peak quantities, and others. Expertise in computer programming and acoustics are necessary for correct data processing and meaningful outputs.

10.1 Schematic representation (sound pressure and particle motion)

A simplified schematic of typical processing steps is shown in Figure 19. The JIP Data Processing Standard (Ainslie et al., 2018b) describes calculations for each step in the processing, and each spectral quantity considers filtering in the frequency domain as illustrated by Figure 19. For each spectral quantity an alternative method is described, involving filtering in the time domain (Ainslie et al., 2018b).

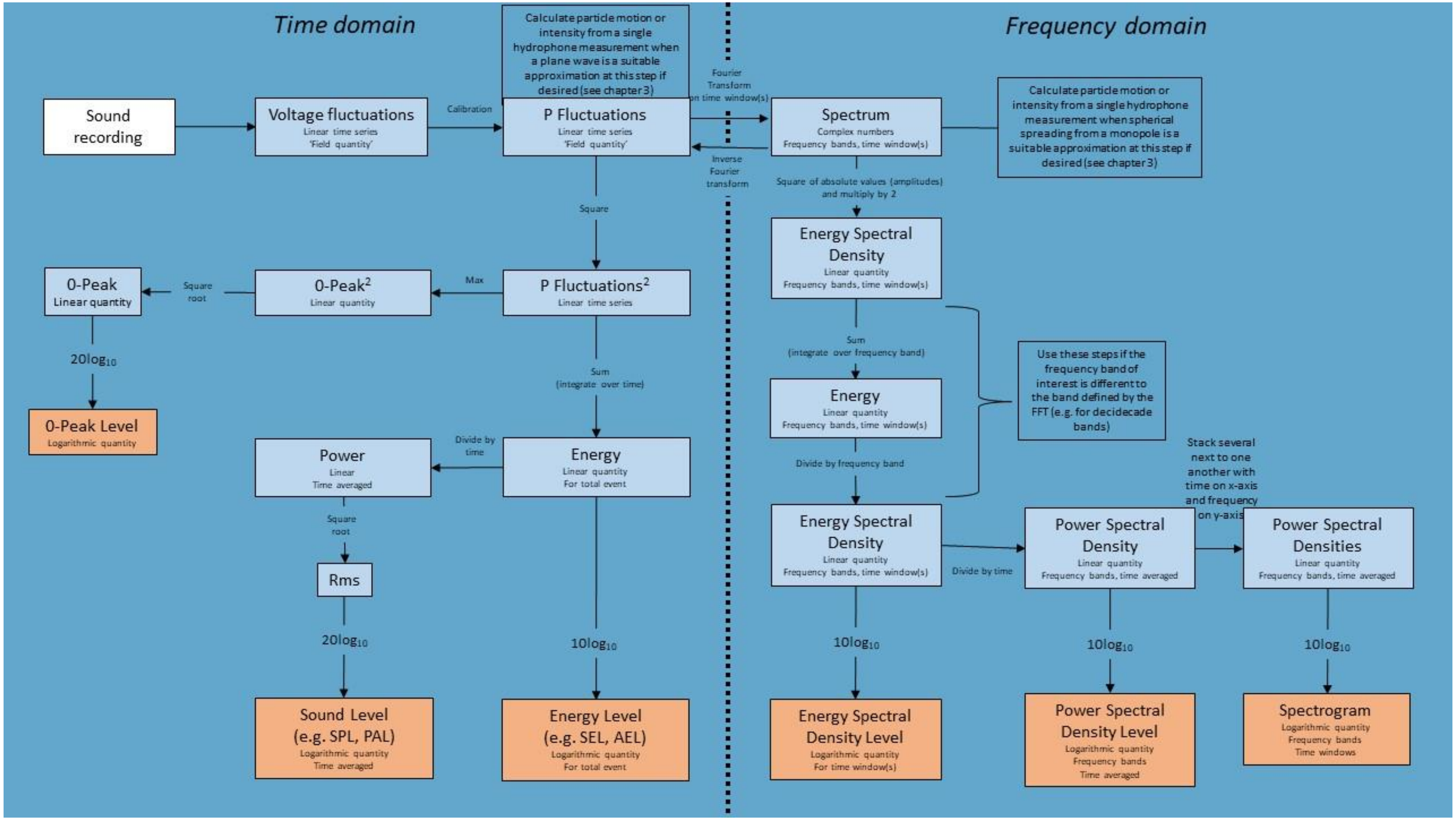


Figure 19 Schematic representation of key steps in digital processing of acoustical recordings. Voltage fluctuations are digitally sampled at discrete time intervals δt, defined by the sample rate of the digital recorder. 'P Fluctuations' represents calibrated time series of $p(t)$, $\boldsymbol{\delta}(t)$, $\boldsymbol{u}(t)$, $\boldsymbol{a}(t)$ or higher time derivatives of the time series, such as snap and jerk (Table A-1). Examples of typical outputs are in orange boxes. See JIP Data Processing Standard for more details (Ainslie et al., 2018b).

10.2 Components of vector field quantities

Field quantities are calibrated time series of sound pressure, particle displacement, particle velocity, particle acceleration, or higher time derivatives (see Figure 19, 'P Fluctuations'). Assuming the recommendation to measure PM in three dimensions has been followed, PM data should be stored as three separate channels relating to the three orthogonal axes x, y and z. Individual components of vector field quantities can be written as $\boldsymbol{\delta}_{\boldsymbol{x}}(t)$, $\boldsymbol{u}_{\boldsymbol{x}}(t)$, $\boldsymbol{a}_{\boldsymbol{x}}(t)$ (replacing x with y or z as appropriate). As an example of how these quantities should be represented during data processing, power (mean-square value) should be shown as (using x axis as an example):

$$\overline{x^2} = \frac{1}{T}\int_0^T x(t)^2 \, \mathrm{d}t, \qquad \text{Equation 50}$$

with digital representation (Ainslie et al., 2018b) as

$$\overline{x_n^2} = \frac{1}{N}\sum_{n=1}^{N} x_n^2 \, . \qquad \text{Equation 51}$$

To calculate the overall magnitude of PM, the three axes (x, y, z) should be integrated using:

$$a = \sqrt{x^2 + y^2 + z^2} \qquad \text{Equation 52}$$

10.3 Sound intensity, equivalent plane wave intensity and active sound intensity

Sound intensity is not included in the scope of the JIP Data Processing Standard (Ainslie et al., 2018b), thus it is introduced here. Sound intensity as a vector quantity is used to determine the bearing of a sound source. Sound intensity is essentially the product of the sound pressure and the PM (Chapter 3 and Equation 61). Sometimes in underwater acoustics, the term "intensity" is used loosely as a synonym of equivalent plane wave intensity (EPWI, symbol I_{eq} see Equation 37). EPWI uses the plane wave approximation of the PM magnitude in place of a measurement of the PM, thus, we discourage this use because it does not include directional information. When using the concept of acoustic intensity, distinguish clearly between sound intensity, average sound intensity and equivalent plane wave intensity.

The mean-square sound pressure and equivalent plane wave intensity (ISO18405:2017) are

$$\overline{p^2} = \frac{1}{T}\int_0^T p(t)^2 \, \mathrm{d}t, \qquad \text{Equation 53}$$

and

$$I_{\mathrm{eq}} = \overline{p^2}/\rho c \, . \qquad \text{Equation 54}$$

respectively. Digital representations of these are (Ainslie et al., 2018b)

$$\overline{{p_n}^2} = \frac{1}{N}\sum_{n=1}^{N} {p_n}^2, \qquad \text{Equation 55}$$

and

$$I_{\text{eq}} = \overline{p_n^2}/\rho c \,, \qquad \text{Equation 56}$$

respectively.

Rather, sound intensity defined as the vector quantity is as follows:

$$\boldsymbol{I}(t) = p(t)\boldsymbol{u}(t). \qquad \text{Equation 57}$$

The sound intensity fluctuates around its mean value over time. Once p(t) and **u**(t) are known separately, then the intensity can be calculated as their product (Equation 57). The basic steps for calculating intensity are described next.

The time-averaged sound intensity is the mean value of the sound intensity. The time-averaged sound intensity is given by

$$\boldsymbol{I}_{\text{av}} = \overline{\boldsymbol{I}(t)} = \frac{1}{T}\int_0^T \boldsymbol{I}(t)\,\mathrm{d}t. \qquad \text{Equation 58}$$

A closely related quantity is the active sound intensity which provides the same approximate value as Equation 58 while eliminating the need for averaging. The active sound intensity is given by

$$\boldsymbol{I}_{\text{a}}(t) = \frac{1}{2}\,\mathrm{Re}\,\left(q_p{}^*(t)\;\boldsymbol{q}_u(t)\right), \qquad \text{Equation 59}$$

where q_p and $\boldsymbol{q}_u$ denote the analytic signals (using complex numbers) of the sound pressure and particle velocity, respectively (see Appendix A, Section A.6 regarding complex numbers and Table A-5). For a sinusoidal sound signal, the active sound intensity is equal to the time-averaged sound intensity when averaged over one or more half-cycles of the sinusoid. Digital implementations of these are:

$$\boldsymbol{I}_{\text{av}} = \frac{1}{N}\sum_{n=0}^{N-1}\boldsymbol{I}_n, \qquad \text{Equation 60}$$

where

$$\boldsymbol{I}_n = p(t_n)\boldsymbol{u}(t_n), \qquad \text{Equation 61}$$

and

$$\boldsymbol{I}_{\text{a}}(t_n) = \frac{1}{2}\,\mathrm{Re}\,\left(q_{p,n}{}^*\;\boldsymbol{q}_{u,n}\right). \qquad \text{Equation 62}$$

The MATLAB™ command 'q = hilbert(x)' returns the analytic signal

$$q_n = x_n + \mathrm{i}h_n, \qquad \text{Equation 63}$$

where h_n is the Hilbert transform of the vector x_n.

A clear distinction should be made between sound intensity, time averaged sound intensity, active sound intensity, and equivalent plane wave intensity. See Appendix A Table A-6.

10.4 Frequency bands

Standard decidecade (one-tenth decade) frequency bands (IEC 61260-1:2014; Ainslie et al., 2018d) should be used for presenting frequency spectra (one decidecade is approximately equal to one third of an octave, and for this reason is sometimes referred to as a “one-third octave”). There is a choice between presenting power or power spectral density, and similarly between energy and energy spectral density. The power spectral density and energy spectral density do not change, on average, if a different frequency bandwidth is used. By comparison, the frequency-integrated quantities (power and energy) are proportional, on average, to bandwidth. The frequency bandwidth and whether power or power spectral density, or energy or energy spectral density are reported shall be made clear.

10.5 Checklist

Requirements and recommendations for data processing are summarised below.

Requirements

- Adopt an existing data processing protocol or develop your own (Section 10).
- Specify whether energy or energy spectral density, or power or power spectral density are used when representing frequency bands (Section 10.4).

Recommendations

- Use the JIP Data Processing Standard (Ainslie et al., 2018b) for processing time series into metrics for power and energy quantities, their spectral densities, zero-to-peak quantities, and others (Section 10.1).
- When using the concept of acoustic intensity, distinguish clearly between sound intensity, average sound intensity and equivalent plane wave intensity (Section 10.3).
- Use standard decidecade bands for energy spectra and power spectra (Section 10.4).

The way that data are reported influences whether they are useful to readers. It is important to make sure data are reported in a way that is correct, consistent, and comparable within and across studies. This chapter describes best practice for reporting PM. We begin by guiding readers to follow existing terminology standards and define any new terminology missing from existing standards. We then describe the best practice that applies to reporting PM data in both linear (e.g., m/s^2) and logarithmic quantities (levels in decibels, or dB). Reporting linear quantities is relatively simple and we therefore have a short section providing specific guidance on how to do this. When it comes to reporting logarithmic quantities (levels) in decibels there are a few key areas where pitfalls are commonly encountered or there is not agreement within the general field of acoustics about best practice. We have gone to some lengths to hear arguments for each option from experts measuring PM from across the globe and as authors arrived at consensus about what we consider to be best practice. We describe what we consider to be best practice and explain the rationale behind our decisions. We follow this with examples of best practice and a summary. Additional guidance on general reporting of acoustics is provided by the JIP Reporting Standard (Ainslie and de Jong, 2018c).

Feedback from a group of experts that reviewed the interim version of this best practice guide was obtained during a webinar on 14 September 2020. This chapter has been updated to reflect the consensus of the authors, taking into account the expert group's feedback. In particular:

- 81 % of participating experts supported the presentation of acceleration, in addition to whatever PM quantity was of direct relevance to the scientific study (velocity, displacement, or other derivatives), to improve compatibility across studies;
- 53 % of participating experts supported the presentation of linear quantities (e.g., sound particle acceleration, in m/s^2) and logarithmic quantities (sound particle acceleration level, in dB), to improve compatibility with other studies (27 % supported linear only and 20 % supported dB only);
- 63 % of participating experts supported the presentation, when reporting a level in dB, of writing the reference value with the quantity symbol
  - New recommendation example: L_a (re 1 µm/s^2) = 50 dB
  - Former way of writing, example: L_a = 50 dB re 1 µm/s^2

11.1 Terminology

The underwater acoustics terminology standard ISO 18405:2017 shall be followed for basic terminology and cited. More advanced terminology will likely be needed for any project involving the measurement of PM. Projects working on PM should follow and cite an existing terminology standard or develop their own. Existing standards for consideration include the JIP Terminology Standard (Ainslie et al., 2018a), the ADEON Terminology Standard (Ainslie et al., 2020) and the JOMOPANS Terminology Standard (Wang and Robinson, 2020). This guide follows the JIP Terminology Standard as well as ISO 18405:2017. When new terminology is introduced, it shall be clearly defined so that others may correctly follow the method, results, and conclusions.

11.2 Reporting linear and logarithmic quantities

Both linear quantities (e.g., particle acceleration in m/s^2, sound intensity in W/m^2) and the corresponding logarithmic quantities (levels e.g., particle acceleration level (PAL; re 1 µm/s^2), sound intensity level (SIL; re 1 pW/m^2), in dB) should be reported.

When direct comparisons between sound pressure and PM are made, they should be between quantities that are both linear or both logarithmic (e.g., particle acceleration in m/s^2 versus sound pressure in Pa or particle acceleration level (re 1 $\mu m/s^2$) in dB versus sound pressure level (re 1 µPa) in dB). We discourage the comparison of sound pressure level in dB with linear PM quantities.

When reporting both linear and logarithmic quantities:

- The nature of the quantity reported shall be made clear (e.g., energy or energy spectral density, or power or power spectral density).
- The coordinate system for reporting vector quantities shall be described (specify the direction of at least two axes and use a right-hand coordinate system).
- The frequency band over which a quantity is integrated or averaged shall be reported.
- The time duration over which a quantity is integrated or averaged shall be reported.
- A frequency breakdown (for example a power or energy spectral density plot) should be reported to improve comparability between studies that focus on biological receivers with different frequency sensitivity ranges.
- Standard decidecade (one-tenth decade) frequency bands (Ainslie et al., 2018d) should be used for reporting frequency spectra (one decidecade is approximately equal to one third of an octave, and for this reason is sometimes referred to as a “one-third octave”).

11.3 Reporting linear quantities

When reporting the value of a linear quantity, there are two important pieces of information to be conveyed, in addition to the numerical value. These are the nature of the quantity (e.g., rms sound particle acceleration) and the unit (e.g., m/s^2). Figure 20 shows examples of how to report linear quantities in yellow (quantity symbol on the left of the equal sign and the unit on the right after the value, as per international standards). Table A-1 in the Appendix A gives the full range of symbols for the natures of quantities and their units. International System of Units (SI) units shall be used for reporting linear quantities. These may be converted to non-SI units in brackets if desired.

Both linear quantities and levels should be reported.

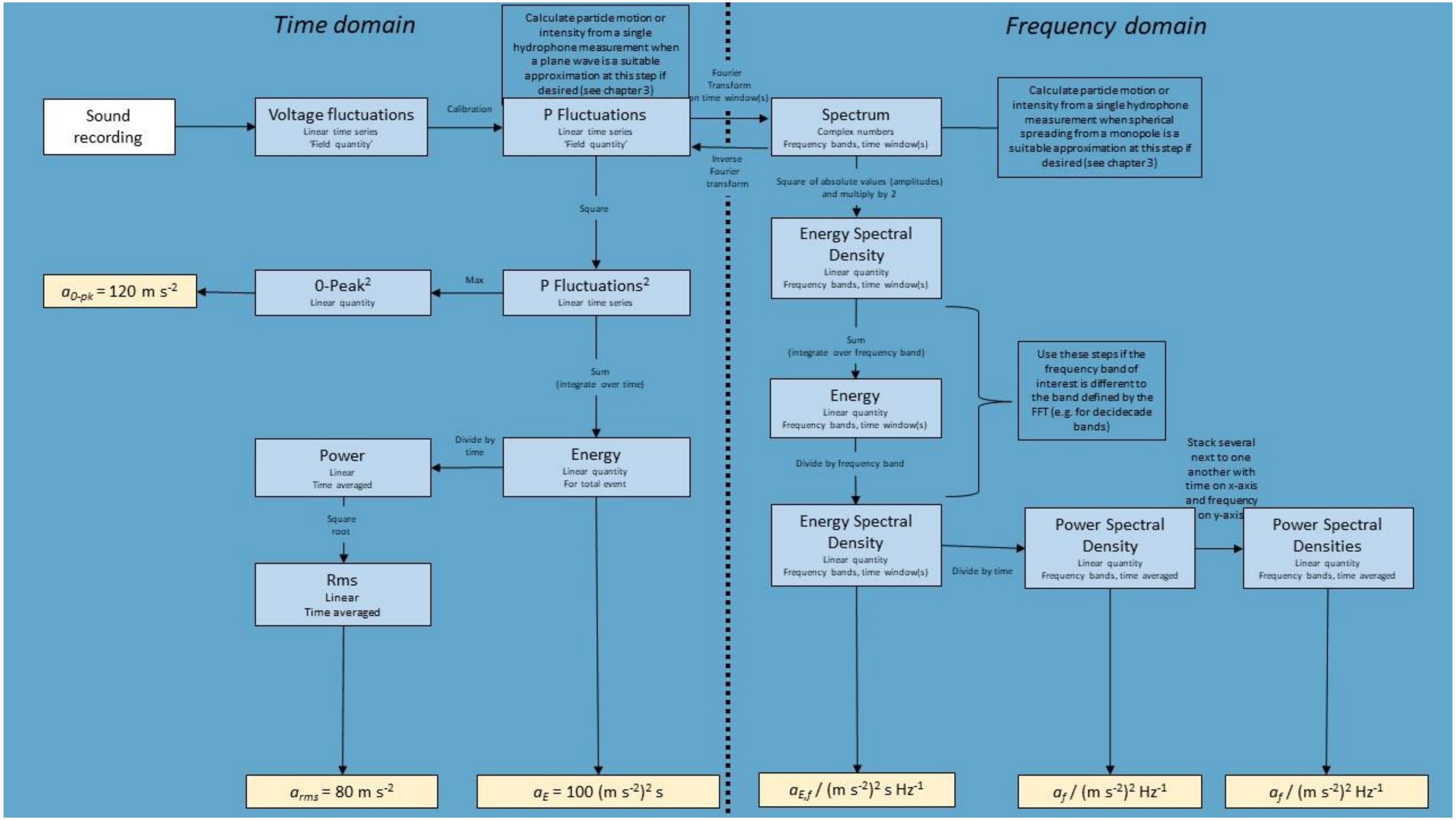


Figure 20 Schematic representation of key steps in digital processing of acoustical recordings including examples of reporting particle acceleration magnitude as **linear quantities** (adapted from Figure 19). Examples of reporting time domain quantities are provided in yellow boxes on the left. In the frequency domain we show an example of the frequency axis title for a graphical representation of quantities across frequencies. See JIP signal processing standard for more details (Ainslie et al., 2018b).

11.4 Reporting levels (using dB units with reference values)

A level is the logarithm of a power ratio. It is as meaningless to state that a level is 20 dB without a reference value, as it is meaningless to state that a power quantity is "100 times greater" without clarifying what the power is greater than. Similarly, it is necessary to state the nature of the power quantity: for example, sound exposure, power spectral density, etc.

When reporting the value of a quantity as a level, in decibels, there are three important pieces of information to be conveyed in addition to the numerical value. These are the nature of the quantity (e.g., rms sound particle acceleration level), the reference value (e.g., 1 μm/s^2) and the unit (dB).

Requirements when quantities are reported as levels:

- Quantity: The power or root-power quantity being expressed in decibels shall be clearly identified. This may be achieved by reference to the appropriate term in Appendix A (Table A-3 and Table A-4), Ainslie et al (2018a) or ISO 18405.
- Reference value: The reference value shall be stated in SI units compatible with ISO 18405:2017, see Table 8 for our recommendations.
- Unit: The level of a power quantity shall be reported in decibels (dB).

See Figure 21 and Section 11.5 for examples of how to report various logarithmic quantities (levels), based on the requirements and recommendations of this guide.

Both linear quantities and levels should be reported.

11.4.1 Choice of reference value

When using decibels, careful consideration should be given to the choice of reference value. There are two different methods for converting linear quantities to decibels and the method that should be used depends on the quantity being reported. The general convention in acoustics is to use the method that results in the simplest reference value that retains all necessary information. We recommend the most widely used convention for each reference to facilitate comparison with the literature (e.g., Southall et al., 2007, 2019; Popper et al., 2014; Dekeling et al., 2014; see Table 8).

One of the methods for converting quantities to decibels is known as the 'power' rule and uses a 10 $\log_{10}$ operation:

$$L_P = 10 \log_{10} \frac{P}{P_0} \text{ dB,}$$ Equation 64

where P is a generic power quantity, which can be in sound pressure or PM (e.g., sound exposure, E). The other rule for converting quantities to decibels is known as the 'root-power' rule and uses 20 $\log_{10}$

$$L_P = 20 \log_{10} \frac{P^{1/2}}{P_0^{1/2}} \text{ dB.}$$ Equation 65

These two equations are mathematically identical, but they lead to different reference values. Specifically, P_0 , e.g., $1 \text{ pm}^2\text{s}$ if P is the sound particle displacement (see Table 6), and $P_0^{1/2}$, e.g., $1 \text{ pm s}^{1/2}$ (see Table 7).

If the power rule is applied consistently, the reference value for derived quantities, created as a sum or difference of levels or level differences, is the product or ratio of the corresponding reference value (Ainslie et al., 2020). The same applies to the root-power rule if applied consistently.

Either the power or root-power rule may be used and be technically correct, but they are rarely applied consistently. Instead, the most widely used convention is to select a method that removes an exponent from the reference value. For example, the power rule (using the $10\log_{10}$ method) is generally used where they simplify the reference value by removing a fractional exponent (e.g., $L_{E,a}$ (re 1 pm^2 s) rather than $L_{E,a}$ (re 1 pm s$^{1/2}$)). However, root-powers (using the $20\log_{10}$ method) are generally used where they simplify the reference value by removing an exponent (e.g., L_a (re 1 µm/s^2) rather than L_a (re 1 (µm/s^2)^2).

Table 6 Power quantity reference values for sound pressure, PM, and sound intensity. Reference values of sound particle jerk (1 mm/s^3) and sound particle snap (1 m/s^4) are proposed. Note $t_0 = 1$ s; $f_0 = 1$ Hz.

Quantity	Power	Energy	Power Spectral Density	Energy Spectral Density
sound pressure ($p_0 = 1$ µPa)	$p_0^2 =$ 1 µPa^2	$p_0^2\, t_0 =$ 1 µPa^2 s	$p_0^2\, f_0^{-1} =$ 1 µPa^2 Hz^{-1}	$\delta_0^2\, t_0 f_0^{-1} =$ 1 µPa^2 s Hz^{-1}
sound particle displacement ($\delta_0 = 1$ pm)	$\delta_0^2 =$ 1 pm^2	$\delta_0^2\, t_0 =$ 1 pm^2 s	$\delta_0^2\, f_0^{-1} =$ 1 pm^2 Hz^{-1}	$\delta_0^2\, t_0 f_0^{-1} =$ 1 pm^2 s Hz^{-1}
sound particle velocity ($u_0 = 1$ nm/s)	${u_0}^2 =$ 1 (nm s^{-1})^2	${u_0}^2\, t_0 =$ 1 (nm s^{-1})^2 s	${u_0}^2\, f_0^{-1} =$ 1 (nm s^{-1})^2 Hz^{-1}	$u_0^2\, t_0 f_0^{-1} =$ 1 (nm s^{-1})^2 s Hz^{-1}
sound particle acceleration ($a_0 = 1$ µm/s^2)	${a_0}^2 =$ 1 (µm s^{-2})^2	${a_0}^2\, t_0 =$ 1 (µm s^{-2})^2 s	${a_0}^2\, f_0^{-1} =$ 1 (µm s^{-2})^2 Hz^{-1}	${a_0}^2\, t_0 f_0^{-1} =$ 1 (µm s^{-2})^2 s Hz^{-1}
sound particle jerk ($j_0 = 1$ mm/s^3)	${j_0}^2 =$ 1 (mm s^{-3})^2	${j_0}^2\, t_0 =$ 1 (mm s^{-3})^2 s	${j_0}^2\, f_0^{-1} =$ 1 (mm s^{-3})^2 Hz^{-1}	${j_0}^2\, t_0 f_0^{-1} =$ 1 (mm s^{-3})^2 s Hz^{-1}
sound particle snap ($\sigma_0 = 1$ m/s^4)	${\sigma_0}^2 =$ 1 (m s^{-4})^2	${\sigma_0}^2\, t_0 =$ 1 (m s^{-4})^2 s	${\sigma_0}^2\, f_0^{-1} =$ 1 (m s^{-4})^2 Hz^{-1}	${\sigma_0}^2\, t_0 f_0^{-1} =$ 1 (m s^{-4})^2 s Hz^{-1}
sound intensity ($i_0 = 1$ pW/m^2)	$i_0 =$ 1 pW m^{-2}	$i_0\, t_0 =$ 1 (pW m^{-2}) s	$i_0\, f_0^{-1} =$ 1 (pW m^{-2}) Hz^{-1}	$i_0\, t_0 f_0^{-1} =$ 1 (pW m^{-2}) s Hz^{-1}

Table 7 Root-power quantity reference values for sound pressure, PM, and sound intensity. Reference values of sound particle jerk (1 mm/s^3) and sound particle snap (1 m/s^4) are proposed. Note $t_0 = 1$ s; $f_0 = 1$ Hz.

Quantity	Root-Power	Root-Energy	Root-Power Spectral Density	Root-Energy Spectral Density
sound pressure ($p_0 = 1$ µPa)	$p_0 =$ 1 µPa	$p_0\, t_0^{1/2} =$ 1 µPa s$^{1/2}$	$p_0\, f_0^{-1/2} =$ 1 µPa Hz$^{-1/2}$	$p_0\, t_0^{1/2} f_0^{-1/2} =$ 1 µPa s$^{1/2}$ Hz$^{-1/2}$
sound particle displacement ($\delta_0 = 1$ pm)	$\delta_0 =$ 1 pm	$\delta_0\, t_0^{1/2} =$ 1 pm s$^{1/2}$	$\delta_0\, f_0^{-1/2} =$ 1 pm Hz$^{-1/2}$	$\delta_0 t_0^{1/2} f_0^{-1/2} =$ 1 pm s$^{1/2}$ Hz$^{-1/2}$
sound particle velocity ($u_0 = 1$ nm/s)	$u_0 =$ 1 nm s^{-1}	$u_0\, t_0^{1/2} =$ 1 (nm s^{-1}) s$^{1/2}$	$u_0\, f_0^{-1/2} =$ 1 (nm s^{-1}) Hz$^{-1/2}$	$u_0\, t_0^{1/2} f_0^{-1/2} =$ 1 (nm s^{-1}) s$^{1/2}$ Hz$^{-1/2}$
sound particle acceleration ($a_0 = 1$ µm/s^2)	$a_0 =$ 1 µm s^{-2}	$a_0 t_0^{1/2} =$ 1 (µm s^{-2}) s$^{1/2}$	$a_0\, f_0^{-1/2} =$ 1 (µm s^{-2}) Hz$^{-1/2}$	$a_0\, t_0^{1/2} f_0^{-1/2} =$ 1 (µm s^{-2}) s$^{1/2}$ Hz$^{-1/2}$
sound particle jerk ($j_0 = 1$ mm/s^3)	$j_0 =$ 1 mm s^{-3}	$j_0\, t_0^{1/2} =$ 1 (mm s^{-3}) s$^{1/2}$	$j_0\, f_0^{-1/2} =$ 1 (mm s^{-3}) Hz$^{-1/2}$	$j_0\, t_0^{1/2} f_0^{-1/2} =$ 1 (mm s^{-3}) s$^{1/2}$ Hz$^{-1/2}$
sound particle snap ($\sigma_0 = 1$ m/s^4)	$\sigma_0 =$ 1 m s^{-4}	$\sigma_0\, t_0^{1/2} =$ 1 (m s^{-4}) s$^{1/2}$	$\sigma_0\, f_0^{-1/2} =$ 1 (m s^{-4}) Hz$^{-1/2}$	$\sigma_0\, t_0^{1/2} f_0^{-1/2} =$ 1 (m s^{-4}) s$^{1/2}$ Hz$^{-1/2}$
sound intensity ($i_0 = 1$ pW/m^2)	$i_0^{1/2} =$ 1 pW$^{1/2}$ m^{-1}	$i_0^{1/2}\, t_0^{1/2} =$ 1 (pW$^{1/2}$ m^{-1}) s$^{1/2}$	$i_0^{1/2}\, f_0^{-1/2} =$ 1 (pW$^{1/2}$ m^{-1})Hz$^{-1/2}$	$i_0^{1/2} t_0^{1/2} f_0^{-1/2} =$ 1 (pW$^{1/2}$ m^{-1}) s$^{1/2}$ Hz$^{-1/2}$

Jerk and snap are omitted from Table 8 because these quantities are not yet widely used in bioacoustics.

Table 8 Recommended reference values for sound pressure, PM and sound intensity using a mixture of power and root-power quantities. Orange shaded cells indicate choice of the root-power ($20 \log_{10} P^{1/2}$ convention. Unshaded cells indicate choice of the power ($10 \log_{10} P$) convention. Note $t_0 = 1$ s; $f_0 = 1$ Hz.

Quantity	Root-Power (for sound pressure or PM) or Power (for intensity)	Energy (Sound exposure)	Power Spectral Density	Energy Spectral Density
sound pressure ($p_0 = 1$ µPa)	$p_0 =$ 1 µPa	${p_0}^2\, t_0 =$ 1 µPa² s	${p_0}^2\, {f_0}^{-1} =$ 1 µPa² Hz⁻¹	${\delta_0}^2\, t_0 {f_0}^{-1} =$ 1 µPa² s Hz⁻¹
sound particle displacement ($\delta_0 = 1$ pm)	$\delta_0 =$ 1 pm	${\delta_0}^2\, t_0 =$ 1 pm² s	${\delta_0}^2\, {f_0}^{-1} =$ 1 pm² Hz⁻¹	${\delta_0}^2\, t_0 {f_0}^{-1} =$ 1 pm² s Hz⁻¹
sound particle velocity ($u_0 = 1$ nm/s)	$u_0 =$ 1 nm s⁻¹	${u_0}^2\, t_0 =$ 1 (nm s⁻¹)² s	${u_0}^2\, {f_0}^{-1} =$ 1 (nm s⁻¹)² Hz⁻¹	${u_0}^2\, t_0 {f_0}^{-1} =$ 1 (nm s⁻¹)² s Hz⁻¹
sound particle acceleration ($a_0 = 1$ µm/s²)	$a_0 =$ 1 µm s⁻²	${a_0}^2\, t_0 =$ 1 (µm s⁻²)² s	${a_0}^2\, {f_0}^{-1} =$ 1 (µm s⁻²)² Hz⁻¹	${a_0}^2\, t_0 {f_0}^{-1} =$ 1 (µm s⁻²)² s Hz⁻¹
sound particle jerk ($j_0 = 1$ mm/s³)	$j_0 =$ 1 mm s⁻³	${j_0}^2\, t_0 =$ 1 (mm s⁻³)² s	${j_0}^2\, {f_0}^{-1} =$ 1 (mm s⁻³)² Hz⁻¹	${j_0}^2\, t_0 {f_0}^{-1} =$ 1 (mm s⁻³)² s Hz⁻¹
sound particle snap ($s_0 = 1$ m/s⁴)	$s_0 =$ 1 m s⁻⁴	${s_0}^2\, t_0 =$ 1 (m s⁻⁴)² s	${s_0}^2\, {f_0}^{-1} =$ 1 (m s⁻⁴)² Hz⁻¹	${s_0}^2\, t_0 {f_0}^{-1} =$ 1 (m s⁻⁴)² s Hz⁻¹
sound intensity ($i_0 = 1$ pW/m²)	$i_0 =$ 1 pW m⁻²	$i_0\, t_0 =$ 1 (pW m⁻²) s	$i_0\, {f_0}^{-1} =$ 1 (pW m⁻²)Hz⁻¹	$i_0\, t_0 {f_0}^{-1} =$ 1 (pW m⁻²) s Hz⁻¹

An empirical rule was followed to construct Table 8 from Table 6 and Table 7: Where Table 6 contains a fractional power, the form of Table 7 was used; otherwise the form of Table 6 was used. Application of this rule requires the reference value to be in the precise form stated, without simplification or substitution of equivalent units. The "without simplification" caveat is needed because (for example) in the last column of Table 7 one could in principle replace 1 pm $s^{1/2}$ $Hz^{-1/2}$ with 1 pm s or 1 pm Hz^{-1}, in which case the root-power reference value no longer contains a fractional power.

International standard reference values (ISO 18405:2017) shall be used of sound pressure (1 µPa), sound particle displacement (1 pm), sound particle velocity (1 nm/s), sound particle acceleration (1 µm/s²). Reference values of sound particle jerk (1 mm/s³) and sound particle snap (1 m/s⁴) are proposed.

11.4.2 How to report the reference value

Expressions like ***L* = 105 dB re 1 µPa** are common in underwater acoustics. The American national standard ANSI S1.8-2016, follows the widely used "dB re" notation, and makes no clear distinction between unit and reference value. Written in this form it seems reasonable to infer that ***L*** is the sound pressure level, whose value expressed in the unit **dB re 1 µPa**, is **105**. The implication of this inference is that if

L_1 = 105 dB re 1 μPa; and

L_2 = 100 dB re 1 μPa; then

$L_1 - L_2$ = 5 dB re 1 μPa. ✗

But the reference value for the difference is not 1 μPa, so where have we gone wrong? The error can be corrected by recognising that **the unit is the decibel** (just "dB", not "dB re 1 μPa"), whereas the reference value 1 μPa which does not belongs with the unit but belongs with the quantity (level). In other words, it is the level (not the decibel) that is relative to 1 μPa. Armed with this insight and following the convention of (IEC, 2002) we can write instead

L_1 (re 1 μPa) = 105 dB

L_2 (re 1 μPa) = 100 dB

L_1 (re 1 μPa) – L_2 (re 1 μPa) = 5 dB, ✓

which is the result we seek. When written in this form it is immediately apparent that if both levels on the left-hand side are relative to the same reference value, the reference value cancels and is therefore omitted from the right-hand side.

This separation of the quantity (level relative to a specified reference value) from the unit, is in accordance with the SI and International System of Quantities (ISQ).

In the ISQ (ISO, 2009):

> "In accordance with basic principles concerning quantity calculus any attachment to a unit name or symbol as means of giving information about the special nature of the quantity or context of measurement under consideration is incorrect (see ISO 31-0, 3.2.1). However, such attachments are still used for levels in telecommunication and in acoustics. It is also common for weighting scales in acoustics. Such supplementary information shall be carried by the quantity, not by the unit."
>
> "When an international symbol for a unit exists, then this, and no other, shall be used.
>
> Any attachment to a unit symbol as a means of giving information about the special nature of the quantity or context of measurement under consideration is not permitted."

Example:

- "$P_{\text{mech}} = 750$ W, not $P = 750\ \text{W}_{\text{mech}}$"

This requirement of ISO (2009) is in accordance with the following extract from the ninth BIPM brochure (BIPM 2019):

> "Unit symbols must not be used to provide specific information about the quantity and should never be the sole source of information on the quantity. Units are never qualified by further information about the nature of the quantity; any extra

information on the nature of the quantity should be attached to the quantity symbol and not to the unit symbol."

Example:

- "The maximum electric potential difference is $U_{\mathrm{max}} = 1000\ \mathrm{V}$ but not $U = 1000\ \mathrm{V_{max}}$."

11.4.3 Recommendations

We recommend that when reporting levels, the reference value should be placed next to the quantity rather than next to the unit (i.e., the 'ref on the left').

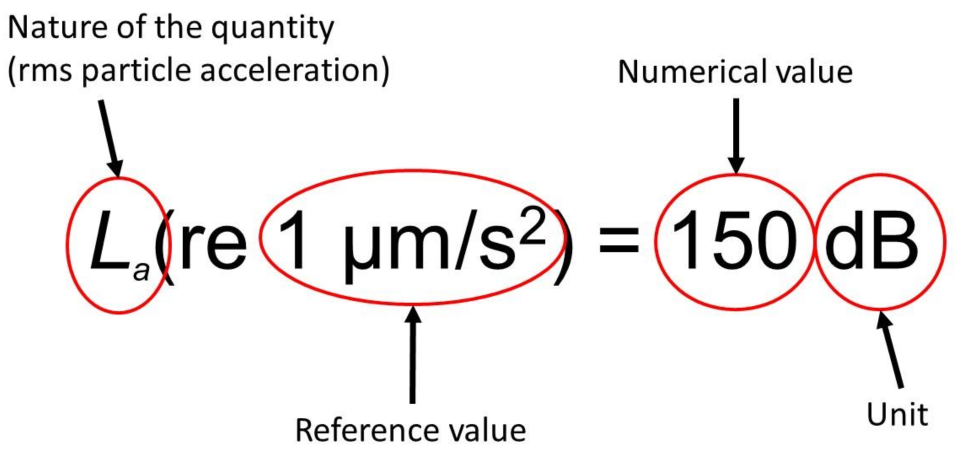


Figure 21 How to report a level in decibels.

The quantity (level relative to a specified reference value) and its unit (decibel) should be clearly distinguished. This distinction is made by following the form of Figure 21, which is compatible with IEC (2002). We therefore recommend following IEC (2002). In this document we follow this international standard throughout.

In accordance with the SI and ISQ rules, attachments to the decibel symbol (dBA, dB re, dB rms) are not permitted because there should be a clear separation between the quantity and the unit.

- $L_{a,\mathrm{rms}}$ (re 1 μm/s^2) = 140 dB, ✓
  - not L_a (re 1 μm/s^2) = 140 dB rms ✗
- $L_{u,\mathrm{pk}}$ (1 nm/s) = 150 dB, ✓
  - not L_u (re 1 nm/s) = 150 dB pk ✗
- $L_{E,p}$ (re 1 μPa^2 s) = 150 dB, ✓
  - not L (re 1 μPa^2 s) = 150 dB SEL ✗

11.5 Examples of reporting particle motion

Examples follow of reporting quantities shown in orange boxes in schematic Figure 22.

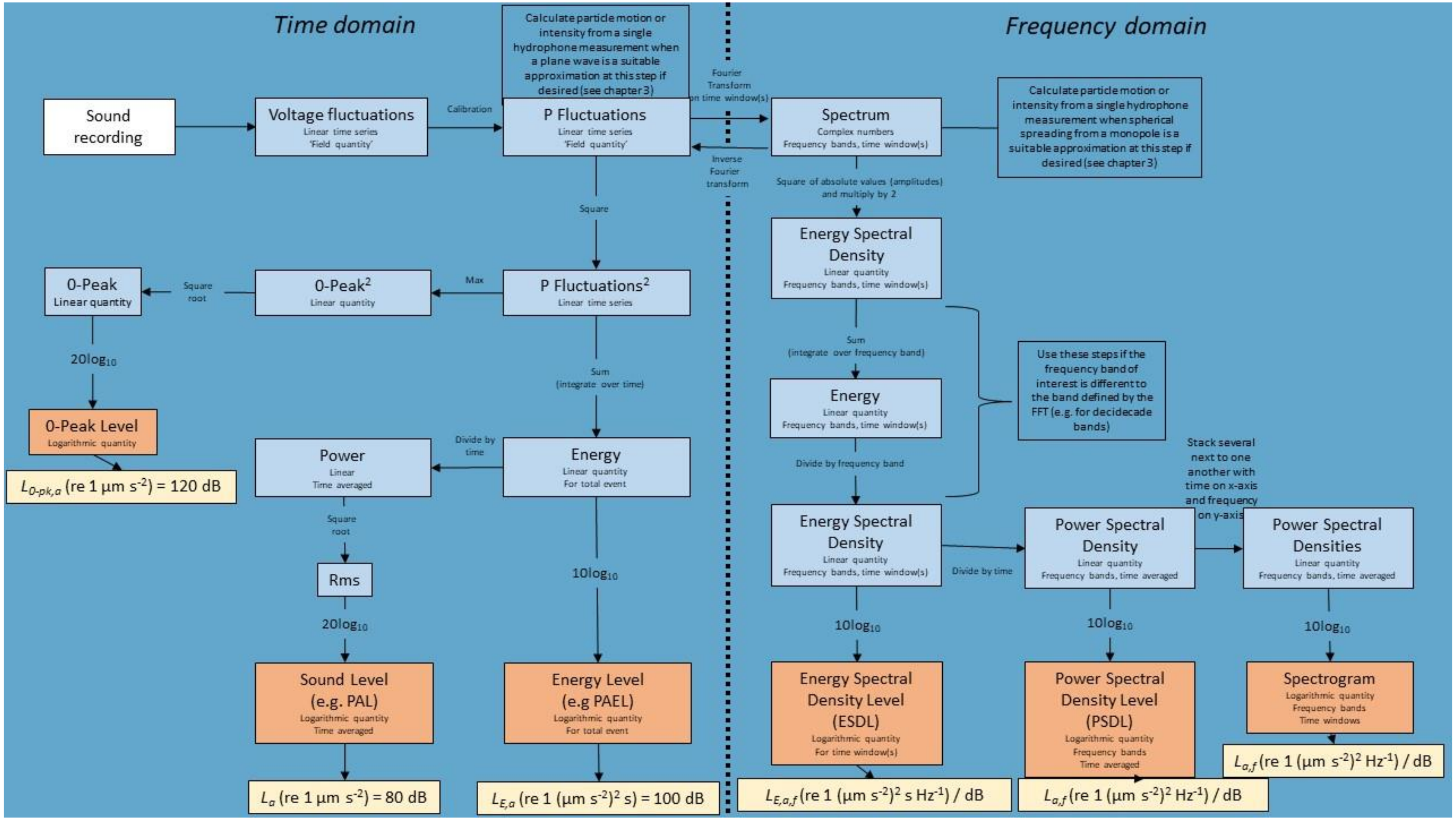


Figure 22 Schematic representation of key steps involved in digital processing of acoustical recordings including examples of reporting **levels** associated with particle motion (adapted from Figure 19). For time domain quantities we show an example of reporting a given level. In the frequency domain we show an example of the frequency axis title for a graphical representation of levels across frequencies. See JIP signal processing standard for more details.

Levels of peak quantities

Zero-to-peak sound pressure (in the frequency band 10-1,000 Hz, for a temporal analysis window of 10 s): 10 Pa

- Zero-to-peak sound pressure level : $L_{p,\mathrm{pk}}$ (re 1 μPa) = 140 dB.

Zero-to-peak sound particle acceleration magnitude (in the frequency band 10-1,000 Hz, for a temporal analysis window of 10 s): 1 cm s^{-2}

- Zero-to-peak sound particle acceleration level: $L_{a,\mathrm{pk}}$ (re 1 μm s^{-2}) = 80 dB

Zero-to-peak sound particle x-acceleration (in the frequency band 10-1,000 Hz, for a temporal analysis window of 10 s): 1 mm s^{-2}

- Zero-to-peak sound particle x-acceleration level: $L_{a,\,,\mathrm{pk},\,x}$ (re 1 μm s^{-2}) = 60 dB

Levels of RMS quantities

Root-mean-square sound pressure (in the frequency band 10 - 1,000 Hz over 30 s): 10 Pa

- Sound pressure level (SPL): L_p (re 1 μPa) = 140 dB

Root-mean-square sound particle y-acceleration (in the frequency band 10 - 1,000 Hz over 30 s): 0.1 mm s^{-2}

- PALy: $L_{a,y}$ (re 1 μm s^{-2}) = 40 dB

Levels of energy quantities

Sound pressure exposure (in the frequency band 10 - 1,000 Hz, for a temporal analysis window of 10 s): 1000 Pa^2 s

- Sound pressure exposure level (SEL): L_E (re 1 μPa^2 s) = 150 dB

Spectrogram

X-axis label: Time / s

Y-axis label: Frequency / Hz

Colour bar label: $L_{a,x,f}$ (re 1 (μm $s^{-2})^2$ Hz^{-1}) / dB

Figure 4. Particle acceleration radial axis spectrogram ($L_{a,x,f}$).

Examples of levels of power (Figure 23) and peak (Figure 24) quantities are provided.

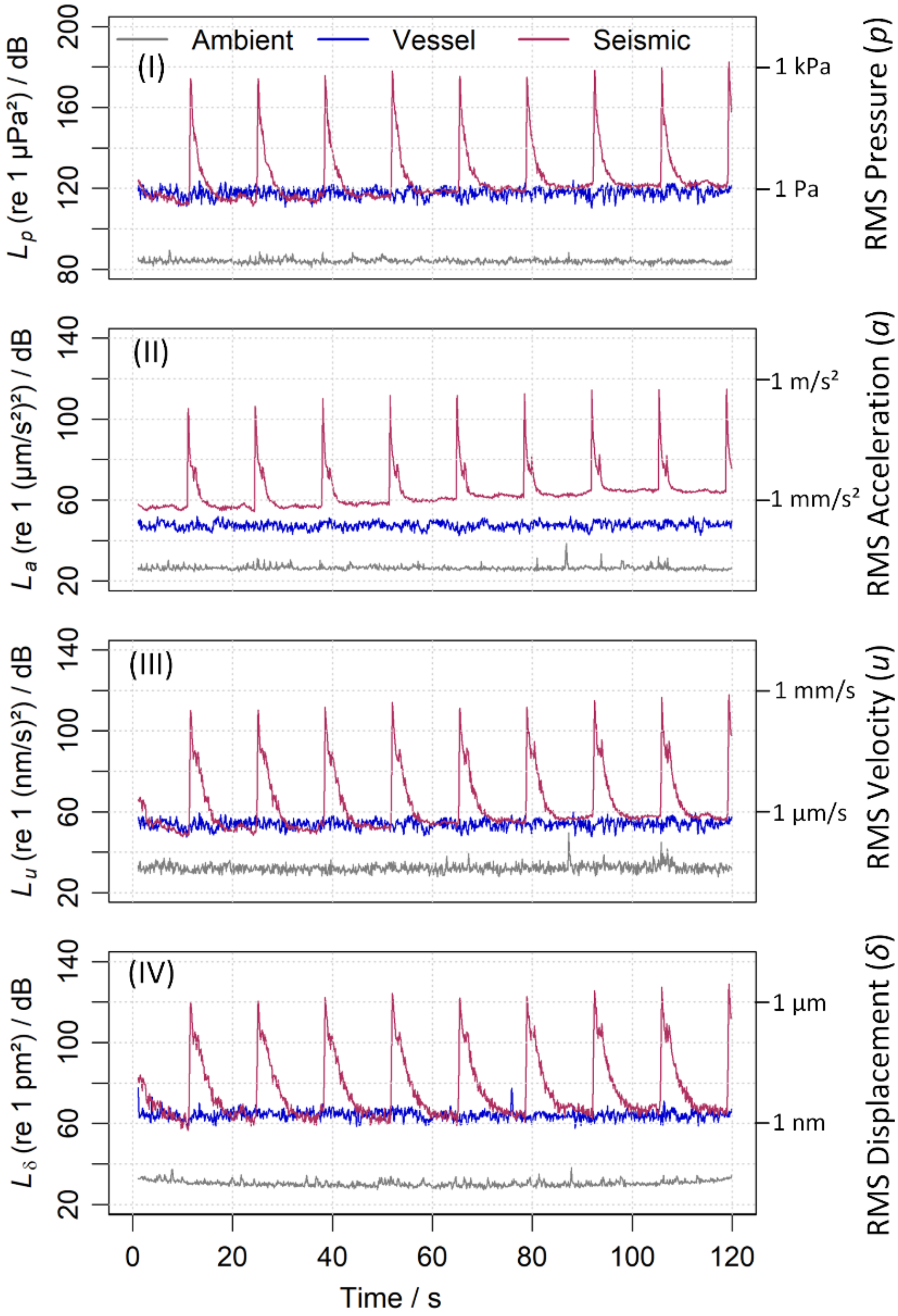


Figure 23 Particle motion quantities (power) vs time. From top to bottom, SPL (L_p re 1 µPa); PAL (L_a re 1 µm/s²); particle velocity level (PVL) (L_u re 1 nm/s); particle displacement level (PDL) (L_δ re 1 pm) versus time. The right-hand axis labels show rms sound pressure, rms sound particle acceleration, rms sound particle velocity, rms sound particle displacement. Averaging time: 100 ms; frequency band: 10-600 Hz. Source: Martin et al. (2021 in prep).

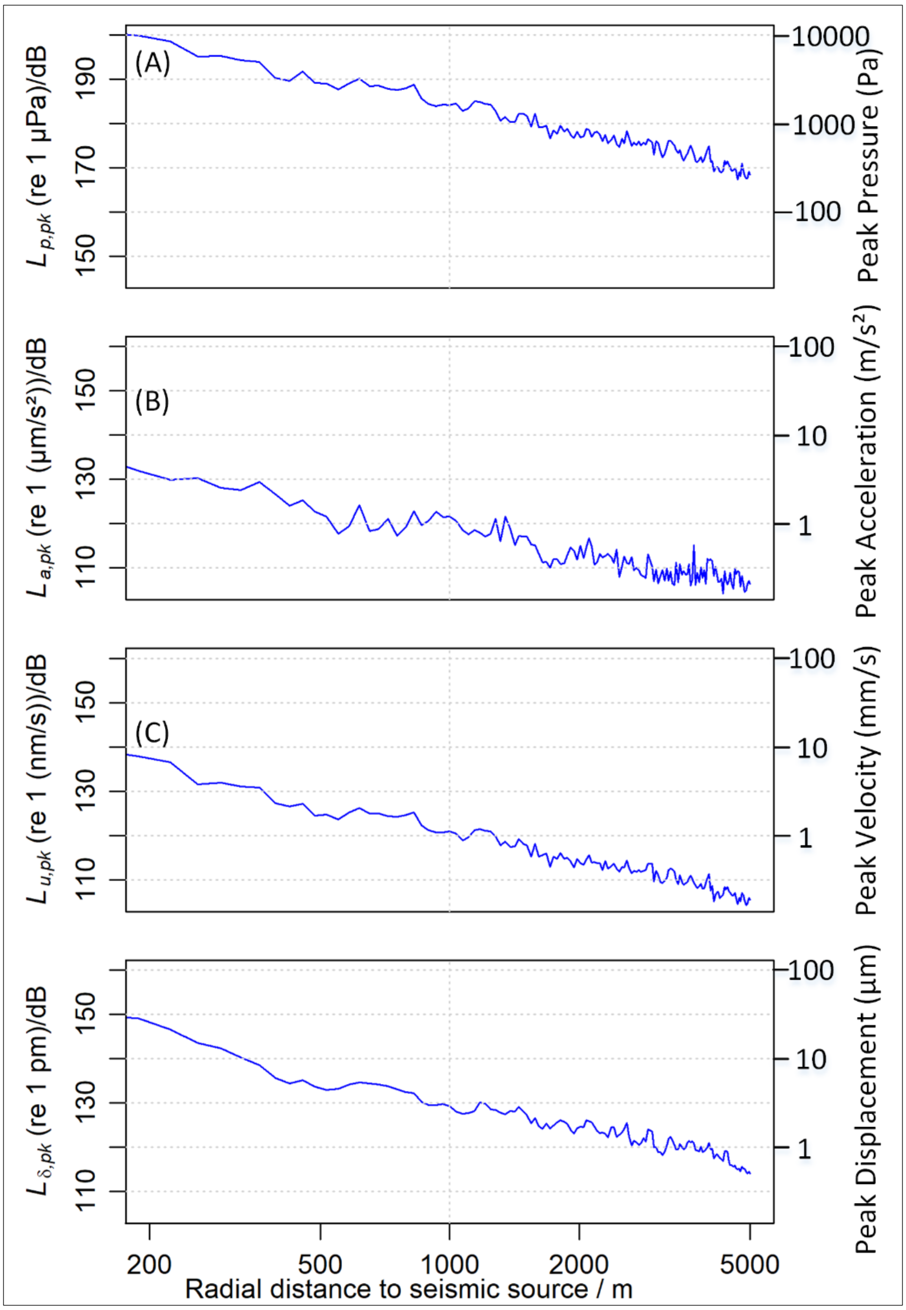


Figure 24 Particle motion quantities (peak) versus range. $L_{p,\mathrm{pk}}$ (re 1 μPa), $L_{a,\mathrm{pk}}$ (re 1 μm/s^2), $L_{u,\mathrm{pk}}$ (re 1 nm/s) and $L_{\delta,\mathrm{pk}}$ (re 1 pm) versus distance. The right-hand axis labels show peak sound particle acceleration, peak sound particle velocity, peak sound particle displacement. Averaging time: 100 ms; frequency band: 10-600 Hz. Source: Martin et al., (2021 *in prep*).

11.6 General remarks on reporting

To ensure inter-project compatibility, because most PM sensors are accelerometers and all fish ears act as accelerometers, acceleration shall be reported alongside any other quantity of interest when possible. The quantity measured by the PM sensor should be reported in addition to any other parameter to which it might be converted. In particular, if particle acceleration is measured using an array of hydrophones, both the sound pressure and acceleration should be reported, while if particle velocity is measured using an accelerometer, both the acceleration and velocity should be reported. Where sound pressure and PM are directly compared, the quantities used should both be either linear or logarithmic. We discourage comparisons between sound pressure in dB with PM as a linear quantity. We recommend making data available to other researchers so that metrics (e.g., PAL) can be calculated over a different frequency band than the one reported. Ideally, all known uncertainties in the measurement system should be listed as a preamble to reporting of acoustic quantities. Doing so provides essential context for comparing with other studies (e.g., how similar was the noise, what was an apparent hearing/damage threshold?) and defining the validity of data-based conclusions. This starts with calibration uncertainty and if relevant, distance between receivers for pressure gradients. This could also include drifts in clocking or gain in the data conditioning/collection electronics. An estimate of the total measurement uncertainty should then be reported. Finally, appropriate use of supplementary material should be made.

11.7 Checklist

Requirements and recommendations for reporting are summarised below.

Requirements

- Follow and cite ISO 18405:2017 for basic terminology. Define new terms where needed (Section 11.1).
- Report the acceleration. This can be in addition to any other metrics relevant to the study (e.g., velocity) (Section 11.6).
- Use SI units for reporting linear quantities (Section 11.3); State the reference value (in SI units, from ISO 18405) when reporting a level in decibels (Section 11.4).
- Describe the co-ordinate system used for reporting vector quantities (Section 11.2).
- Specify the frequency band and the averaging time (Section 11.2).
- When reporting a level in decibels (Section 11.4):
    - Report the level of a power or root-power quantity in decibels (dB);
    - Identify the quantity being expressed in decibels;
    - State the reference value in SI units. The reference value shall be either a power quantity (Table 6) or a root-power quantity (Table 7) (note that our recommendation is the specific combination in Table 8).

Recommendations

- Adopt or develop a terminology standard (Section 11.1).
- Report both linear quantities (e.g., particle acceleration in $\mu m/s^2$, sound intensity in W/m^2) and the corresponding logarithmic quantities (PAL, SIL) in dB (Section 11.2).
- When reporting a level in decibels, place the reference value on the left of the equation, as in Figure 21 (Section 11.4).
- When reporting a level in decibels, state the reference value according to Table 8.
- Report the quantity measured by the PM sensor in addition to any other parameter to which it might be converted (Section 11.6).
- Where sound pressure and PM are directly compared, the quantities used should both be either linear or logarithmic (Section 11.6).
- Make data available to other researchers so that metrics (e.g., PAL) can be calculated over a different frequency band than the one reported (Section 11.6).
- List all known uncertainties in the measurement system (Section 11.6).
- Make use of supplementary material where appropriate (Section 11.6).

12 Summary, or 'nine steps to success'

Our requirements and recommendations for measuring underwater sound PM for biological applications are outlined here. *Requirements* are the essential instructions for avoiding error and are indicated by the word 'shall'. *Recommendations* are the informed views of the authors on best practice and are indicated by the word 'should'. The reasoning behind the requirements and recommendations is provided in the cited sections of the best practice guide.

12.1 Determine the measurement need

If PM is biologically relevant it should be reported. Ask a biologist and refer to Section 1.3 of this guide to establish whether PM is biologically relevant.

If you are only interested in the magnitude (and not the direction) of the PM, you may be able to calculate it from pressure measurements rather than measuring it directly. Ask an acoustician and refer to Chapters 3 and 4 of this guide (background on pm and when to measure).

Requirements

- Report PM or intensity using one of the methods in Chapter 4 when they are biologically relevant (see Section 1.3).
- If calculating PM or EPWI from sound pressure measurements from a single hydrophone while in the near field, check that a monopole is a suitable approximation (see Section 4.1).
- If calculating PM or EPWI from sound pressure measurements from a single hydrophone, check that a plane wave is a suitable approximation (see Section 4.1).
- If using sound pressure differentials to calculate PM or intensity, check hydrophone separation, calibration, and temporal synchronisation of recordings (see Section 4.3).
- If measuring PM with an accelerometer (or other PM sensor), check that the sensor is small relative to the wavelength of the highest frequency to be measured (Section 4.4).

Recommendations

- If a plane wave or spherical spreading from a monopole source are not suitable approximations, measure PM using either the pressure gradient method, an accelerometer or other PM sensor.
- Calculate the intensity as the sound pressure and velocity product if PM has been measured.

12.2 Build a measurement team

You will need people with the following expertise:

- Biology (specifically the acoustic ecology of fishes and aquatic invertebrates)
- Physics (specifically underwater acoustics)
- Computer programming (specifically MATLAB^{TM}, R, Python or other similar)
- PM sensors

Refer to Section 1.4 of this guide.

12.3 Select instrumentation

Select an instrument with an appropriate size, shape, buoyancy, suspension method and sensitivity for your application and circumstances. Refer to Chapter 7 for details on sensor specifications.

Requirements

- Select appropriate PM sensor type and measurement system for the type of measurement being conducted.
- Match the sound level and frequency range of the planned measurement appropriately with the sensor type and system, accounting for frequency response, directivity, dynamic range, and self-noise.
- Consult an expert in underwater acoustics and PM sensors for advice on appropriate instrumentation.

Recommendations

- System clock drift is an issue for autonomous data loggers, account for time synchronization of system clocks using GPS or atomic clocks (Section 7.7).

12.4 Calibrate the measurement system

Ensure the system, end to end, is fully calibrated according to Section 8 including the sensor in suspension.

Requirements

- Calibrate the sound PM sensor over the frequency range of interest (Section 8.1).
- Include the phase response with the calibration (Section 8.3.6).
- Provide an uncertainty with the calibration (Section 8.4).
- State the sensitivity in S.I. units (Section 8.4).
- Report the suspension method used for the sensor calibration and as far as possible use the same method in the field measurements (Section 8.4).

Recommendations

- The calibration certificate should also state: date of the calibration; water temperature; depth of immersion; orientation of the sensor (Section 8.4).
- Where possible, the calibration should be traceable to recognised standards (Section 8.1).

12.5 Plan the deployment

Make sure you plan to make recordings that will represent what it is you want to record as fully as possible, this may mean averaging over several replicates. Plan conservatively so that you are likely to have useful data if an equipment failure or adverse weather event occurs partway through the deployment. Refer to Chapter 9 during the planning stage (Particle motion measurements in open water and tanks).

Consider the following:

- Sources: where, how many, how often, for how long?
- Receivers: place PM sensors in locations where the biological receivers of interest may be found, be aware that biological receivers may be moving around.
- Time: diel, lunar, seasonal and other cycles may influence the activity of biological receivers, ensure recordings are going to be long enough to represent the temporal variability of the signals of interest.
- Space: separation of the sources and receivers, the propagation conditions, the structure of the benthos, water depth, etc.

12.6 Deploy and record

Isolate the sensor from vibrations other than those you wish to measure (e.g., surface waves, substrate vibrations). Refer to Section 9 (measurements in open water and in tanks).

Requirements

- Use sensors and instrumentation with the required performance (Section 9.2)
- Ensure sensors and instrumentation are calibrated to traceable standards (Section 9.3)
- Mount the sensors with a suitable suspension framework suitable for the environmental conditions and the rig design (Section 9.4.2)
- Document the details of sensor specification, suspension, measurements geometry and settings (Section 9.4.2).
- Record all metadata required to describe the experimental context and environment (Section 9.4, 9.5)

12.7 Back up data and metadata

Make sure data are backed up in a way that allows a return to the data to ask different questions (e.g., calculate different metrics, or use different frequency bands). The original time series plus calibration information should be stored.

Recommendations

- Make a backup of raw data at the first opportunity, possibly on site. Copy the measurements protocol and meta data to the same location as raw data.

12.8 Analyse data

Refer to Chapter 10 (data processing).

Requirements

- Adopt an existing data processing protocol or develop your own (Section 10).
- Specify whether energy or energy spectral density, or power or power spectral density are used when representing frequency bands (Section 10.4).

Recommendations

- Use the JIP Data Processing Standard (Ainslie et al., 2018b) for processing time series into metrics for power and energy quantities, their spectral densities, zero-to-peak quantities, and others (Section 10.1).
- When using the concept of acoustic intensity, distinguish clearly between sound intensity, average sound intensity and equivalent plane wave intensity (Section 10.3).
- Use standard decidecade bands for energy spectra and power spectra (Section 10.4).

12.9 Report data

Reporting needs to be correct, consistent, and comparable. Refer to Chapter 11 (Reporting).

Requirements

- Follow and cite ISO 18405:2017 for basic terminology. Define new terms where needed (Section 11.1).
- Report the acceleration. This can be in addition to any other metrics relevant to the study (e.g., velocity) (Section 11.6).
- Use SI units for reporting linear quantities (Section 11.3); State the reference value (in SI units, from ISO 18405) when reporting a level in decibels (Section 11.4).
- Describe the co-ordinate system used for reporting vector quantities (Section 11.2).
- Specify the frequency band and the averaging time (Section 11.2).
- When reporting a level in decibels (Section 11.4):
    - Report the level of a power or root-power quantity in decibels (dB);
    - Identify the quantity being expressed in decibels;
    - State the reference value in SI units. The reference value shall be either a power quantity (Table 6) or a root-power quantity (Table 7) (note that our recommendation is the specific combination in Table 8).

Recommendations

- Adopt or develop a terminology standard (Section 11.1).
- Report both linear quantities (e.g., particle acceleration in $\mu m/s^2$, sound intensity in W/m^2) and the corresponding logarithmic quantities (PAL, SIL) in dB (Section 11.2).
- When reporting a level in decibels, place the reference value on the left of the equation, as in Figure 21 (Section 11.4).
- When reporting a level in decibels, state the reference value according to Table 8.
- Report the quantity measured by the PM sensor in addition to any other parameter to which it might be converted (Section 11.6).
- Where sound pressure and PM are directly compared, the quantities used should both be either linear or logarithmic (Section 11.6).
- Make data available to other researchers so that metrics (e.g., PAL) can be calculated over a different frequency band than the one reported (Section 11.6).
- List all known uncertainties in the measurement system (Section 11.6).
- Make use of supplementary material where appropriate (Section 11.6).

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APPENDICES

Appendix A: Terms and Definitions

A.1 TERMS AND DEFINITIONS

This section introduces and defines the terms used in this good practice guide (Table A-1). It uses terms and definitions previously defined in the Sound and Marine Life JIP terminology standard (Ainslie et al., 2018a). The JIP terminology standard follows ISO 18405:2017 Underwater Acoustics – Terminology, and all definitions are also compatible with ISO 18405:2017.

A.2 General concepts

For general concepts see Figure 1 and Table A-1.

Table A-1 Definitions of terms used in this best practice guide

Term	Definition
A-1.1 amplitude	maximum departure from a variable's equilibrium value
A-1.2 vector	quantity with both magnitude and direction
A-1.3 level	logarithm of a power ratio NOTE: Level is usually expressed in units of decibel (dB)
A-1.4 intensity	power transferred per unit area. NOTE: There are various types of intensity in acoustics, defined in Table A-6
A-1.5 geometric near field	region close to a sound source within which the distances of different source elements from the field point cannot be treated as equal SOURCE: modified from Morfey (2000), p174 NOTE: In the geometric near field the contribution from each source element cannot be adequately represented by weighting according to the reciprocal of the distance to the centre of the source region.
A-1.6 Fresnel near field	region far enough from a sound source to be outside the geometric near field, but not far enough for the Fresnel correction to be neglected SOURCE: modified from Morfey (2000), p 167 NOTES: In the Fresnel near field the sound pressure amplitude is not inversely proportional to range. For a definition of *Fresnel correction*, see Morfey (2000).
A-1.7 hydrodynamic near field	region close to a sound source within which the particle velocity and the pressure are nearly in quadrature SOURCE: modified from Morfey (2000), p189 NOTES: • See also Morse and Ingard, p311, • Two fluctuating fields are said to be in quadrature when one leads the other by a phase difference of $\pi/2$ (90°), meaning that when one is at a maximum the other is passing through zero. For example, a sine wave and a cosine wave are in quadrature.
A-1.8 hydrodynamic far field	region far enough from a point source for effects associated with its hydrodynamic near field to be negligible

Term	Definition
A-1.9 acoustic far field	spatial region in a uniform medium where the direct-path field amplitude, compensated for absorption loss, varies inversely with range SOURCE: ISO 18405
A-1.10 point monopole **Synonym**: monopole	acoustic source density that is concentrated at a single point in space and proportional to a Dirac delta function in space SOURCE: modified from Morfey (2000), p285 NOTES: A point monopole radiates acoustic power uniformly in all directions. For a definition of *Dirac delta function*, see Morfey (2000).
A-1.11 material element **Synonym**: sound particle	smallest element of the medium that represents the medium's mean density SOURCE: ISO 18405:2017
A-1.12 sound pressure **Symbol**: p **Unit**: Pa	contribution to total pressure caused by the action of sound SOURCE: ISO 18405:2017
A-1.13 sound particle displacement **Symbol**: $\boldsymbol{\delta}$ **Unit**: m	displacement of a material element caused by the action of sound SOURCE: ISO 18405:2017
A-1.14 sound particle velocity **Symbol**: $\boldsymbol{u}$ **Unit**: m/s	contribution to velocity of a material element caused by the action of sound SOURCE: ISO 18405:2017 NOTE; Velocity is the rate of change of displacement.
A-1.15 sound particle acceleration **Symbol**: $\boldsymbol{a}$ **Unit**: m/s^2	contribution to acceleration of a material element caused by the action of sound SOURCE: ISO 18405:2017 NOTE; Acceleration is the rate of change of velocity.
A-1.16 sound particle jerk **Symbol**: $\boldsymbol{j}$ **Unit**: m/s^3	contribution to jerk of a material element caused by the action of sound BASED ON: ISO 18405:2017 NOTE; Jerk is the rate of change of acceleration.
A-1.17 sound particle snap **Symbol**: $\boldsymbol{\sigma}$ **Unit**: m/s^4	contribution to snap of a material element caused by the action of sound BASED ON: ISO 18405:2017 NOTE; Snap is the rate of change of jerk.
A-1.18 sound pressure spectrum **Symbol**: P **Unit**: Pa/Hz	Fourier transform of the sound pressure SOURCE: ISO 18405:2017

Term	Definition
A-1.19 sound particle displacement spectrum **Symbol**: $\boldsymbol{\Delta}$ **Unit**: m/Hz	Fourier transform of the sound particle displacement SOURCE: ISO 18405:2017
A-1.20 sound particle velocity spectrum **Symbol**: $\boldsymbol{U}$ **Unit**: m s^{-1}/Hz	Fourier transform of the sound particle velocity SOURCE: ISO 18405:2017
A-1.21 sound particle acceleration spectrum **Symbol**: $\boldsymbol{A}$ **Unit**: m s^{-2}/Hz	Fourier transform of the sound particle acceleration SOURCE: ISO 18405:2017
A-1.22 sound particle jerk spectrum **Symbol**: $\boldsymbol{J}$ **Unit**: m s^{-3}/Hz	Fourier transform of the sound particle jerk SOURCE: ISO 18405:2017
A-1.23 sound particle snap spectrum **Symbol**: $\boldsymbol{\Sigma}$ **Unit**: m s^{-4}/Hz	Fourier transform of the sound particle snap SOURCE: ISO 18405:2017
A-1.24 complex impedance **Symbol**: Z **Unit**: Pa m/s	ratio of sound pressure spectrum to the magnitude of the sound particle velocity spectrum

The convention followed in Table A-1 is to indicate a time-domain quantity with a lower-case letter symbol (e.g., $\boldsymbol{\delta}(t)$ for sound particle displacement) and a frequency domain quantity with an upper case letter symbol (e.g., $\boldsymbol{A}(f)$ for sound particle acceleration spectrum). Further, quantity symbols are in italic font, while abbreviations are upright. Finally, vectors are bold (e.g., $\boldsymbol{U}(f)$ for sound particle velocity spectrum) and scalars (e.g., $p(t)$ for sound pressure) are not.

A.3 Particle motion and vector quantities

Particle motion (PM) is a generic term used to describe sound particle displacement and its time derivatives (velocity, acceleration, jerk, snap, etc). Jerk and snap are not widely used in practice, interest is often limited to displacement $\boldsymbol{\delta}$, velocity $\boldsymbol{u}$ and acceleration $\boldsymbol{a}$. These are all vector quantities (having a magnitude and a direction). Components The three-dimensional nature of vectors is represented by the components along three orthogonal axes, which are indicated by attaching a subscript x, y, z to the usual vector symbol (Table A-2).

A right-handed coordinate system shall be used for vector quantities. The coordinate system shall be clearly specified, preferably with the aid of a drawing. The z axis should point vertically down so that positive values on the z axis indicate depth below the origin and negative values indicate height above it (in the air if the origin is at the sea surface).

Table A-2 Recommended symbols for sound pressure and widely used quantities associated with particle motion and sound intensity.

Characteristic	Pressure	Displacement	Velocity	Acceleration	Intensity
vector (bold, italic)	na	$\boldsymbol{\delta}$	$\boldsymbol{u}$	$\boldsymbol{a}$	$\boldsymbol{I}$
magnitude (italic)	p	δ	u	a	I
x component	na	δ_x	u_x	a_x	I_x
y component	na	δ_y	u_y	a_y	I_y
z component	na	δ_z	u_z	a_z	I_z

A.4 Power, Root-Power and Field Quantities

Of the quantities listed in Table A-2, the mean-square value of the first four (p, δ, u, a) is proportional to sound power or sound intensity. Quantities with this property may be referred to as "field quantities". Sound intensity is a power quantity. Quantities proportional to the square root of power are root-power quantities.

A.5 Power, Energy, and their Spectral Densities

We are used to dealing with spectral densities associated with sound pressure. Sound pressure, power, energy and the spectral densities of these can be presented either as linear quantities (e.g., sound exposure) or logarithmic ones (e.g., sound exposure *level*). Linear quantities are expressed in SI units (Pa^2 s) while levels are expressed in decibels (dB). Linear quantities are always needed for processing, while for some applications levels are often reported. Thus, the linear quantities are always a step in the calculation of levels. Spectral densities refer to the contribution to a power quantity per unit of bandwidth.

In Table A-3 the terms "power" and "energy" are used as shorthand for "power quantity" and "time-integrated power quantity", respectively. Similar, "power spectral density" (abbreviated PSD) (or "energy spectral density", ESD) indicates the "power" (or "energy") in a specified frequency band divided by its bandwidth. See Ainslie et al (2018b) for processing steps required for evaluating PSD and ESD.

ESD (see clause 3.1.3.9 of ISO 18405) of a field variable x is the distribution as a function of non-negative frequency of the time-integrated x^2 per unit bandwidth of a sound having a continuous spectrum. The ESD is related to the energy according to Plancherel's theorem.

$$\int_{-\infty}^{+\infty} x(t)^2 \,\mathrm{d}t = \int_{0}^{+\infty} E_x(f) \,\mathrm{d}f. \qquad \text{Equation 66}$$

where

$$E_x(f) = 2|X(f)|^2. \qquad \text{Equation 67}$$

Equation 66 provides a useful numerical check on the numerical value of ESD. See also Note 4 to entry 3.1.3.9 of ISO 18405.

PSD (see clause 3.1.3.13 of ISO 18405) of a field variable x is the distribution as a function of non-negative frequency of the mean-square value of x per unit bandwidth of a sound having a continuous spectrum.

Table A-3 Recommended variable names and symbols.

Variable Name	Sound Pressure	Displacement	Velocity	Acceleration
power	mean-square sound pressure[1], $\overline{p^2}$	mean-square sound particle displacement[2], $\overline{\delta^2}$	mean-square sound particle velocity[3], $\overline{u^2}$	mean-square sound particle acceleration[4], $\overline{a^2}$
energy	sound pressure exposure (synonym: sound exposure), E_p	sound particle displacement exposure, E_δ	sound particle velocity exposure, E_u	sound particle acceleration exposure, E_a
power spectral density (PSD)	mean-square sound pressure spectral density, $\overline{p_f^2}$	mean-square sound particle displacement spectral density, $\overline{\delta_f^2}$	mean-square sound particle velocity spectral density, $\overline{u_f^2}$	mean-square sound particle acceleration spectral density, $\overline{a_f^2}$
energy spectral density (ESD)	sound pressure exposure spectral density, $E_{p,f}$	sound particle displacement exposure spectral density, $E_{\delta,f}$	sound particle velocity exposure spectral density, $E_{u,f}$	sound particle acceleration exposure spectral density, $E_{a,f}$
rms	root-mean-square sound pressure, p_{rms}	root-mean-square sound particle displacement, δ_{rms}	root-mean-square sound particle velocity, u_{rms}	root-mean-square sound particle acceleration, a_{rms}
peak	zero-to-peak sound pressure, $p_{0-\mathrm{pk}}$	zero-to-peak sound particle displacement, $\delta_{0-\mathrm{pk}}$	zero-to-peak sound particle velocity, $u_{0-\mathrm{pk}}$	zero-to-peak sound particle acceleration, $a_{0-\mathrm{pk}}$

1. The square root of the mean-square sound pressure is a field quantity known as the root-mean-square sound pressure. This field quantity may be denoted p_{rms}. The two quantities are related according to $\overline{p^2} = p_{\mathrm{rms}}^2$.
2. The square root of the mean-square sound particle velocity is a field quantity known as the root-mean-square sound particle velocity. This field quantity may be denoted δ_{rms}. The two quantities are related according to $\overline{\delta^2} = \delta_{\mathrm{rms}}^2$.
3. The square root of the mean-square sound particle velocity is a field quantity known as the root-mean-square sound particle velocity. This field quantity may be denoted u_{rms}. The two quantities are related according to $\overline{u^2} = u_{\mathrm{rms}}^2$.
4. The square root of the mean-square sound particle acceleration is a field quantity known as the root-mean-square sound particle acceleration. This field quantity may be denoted a. The two quantities are related according to $\overline{a^2} = a_{\mathrm{rms}}^2$.

Widely encountered spectral densities include the sound pressure exposure spectral density and the mean-square sound pressure spectral density, often abbreviated as “energy spectral density” (ESD) and “power spectral density” PSD, respectively. For PM we need to distinguish not only between the different varieties of motion (mainly $\boldsymbol{\delta}$, $\boldsymbol{u}$, $\boldsymbol{a}$) but also between the magnitude of these and their components. It gets tedious to redefine these each time they are used so having standard names and symbols for these quantities will help us in reporting the results of our research.

The quantities listed in Table A-3 are all scalars. They are all defined in the JIP terminology standard (Ainslie et al., 2018a) in terms of the magnitude of a vector (except sound pressure, which is already a scalar). Analogous quantities can be constructed for the components of a vector (Table A-4).

Table A-4 Recommended variable names and symbols: components of vector quantities. Examples in the table are for the x component. Symbols for the y or z component are obtained by replacing 'x' with 'y' or 'z'.

Variable Name	Displacement	Velocity	Acceleration
power	mean-square sound particle x-displacement, $\delta^2_{x,\mathrm{rms}}$	mean-square sound particle x-velocity, $u^2_{x,\mathrm{rms}}$	mean-square sound particle x-acceleration, $a^2_{x,\mathrm{rms}}$
energy	sound particle x-displacement exposure, $E_{\delta,x}$	sound particle x-velocity exposure, $E_{u,x}$	sound particle x-acceleration exposure, $E_{a,x}$
power spectral density (PSD)	mean-square sound particle x-displacement spectral density, $\overline{\delta^2_{x,f}}$	mean-square sound particle x-velocity spectral density, $\overline{u^2_{x,f}}$	mean-square sound particle x-acceleration spectral density, $\overline{a^2_{x,f}}$
energy spectral density (ESD)	sound particle x-displacement exposure spectral density, $E_{\delta,x,f}$	sound particle x-velocity exposure spectral density, $E_{u,x,f}$	sound particle x-acceleration exposure spectral density, $E_{a,x,f}$
rms	root-mean-square sound particle x-displacement, x,rms	root-mean-square sound particle x-velocity, $u_{x,\mathrm{rms}}$	root-mean-square sound particle x-acceleration, $a_{x,\mathrm{rms}}$
peak	zero-to-peak sound particle x-displacement, $\delta_{x,0-\mathrm{pk}}$	zero-to-peak sound particle x-velocity, $u_{x,0-\mathrm{pk}}$	zero-to-peak sound particle x-acceleration, $a_{x,0-\mathrm{pk}}$

The information in Table A-4 could have been incorporated into Table A-3. However, doing so would have obscured the link with corresponding levels in decibels (Table A-9).

Root-mean square and peak values are indicated by adding a subscript "rms" or "0-pk" subscript (abbreviations are upright). For example

- rms magnitude of sound particle displacement: δ_{rms}
- peak z component of sound particle acceleration: $a_{z,\text{0-pk}}$
- ESD of the x-component of displacement: $E_{\delta,x,T}$

A.6 Complex representation of field quantities

A.6.1 Sine waves

What are complex numbers and why do we use them? Complex numbers are a way of bridging the gap between the measured fluctuating field quantity and the concept of a constant amplitude at a given frequency. They are produced by the Fourier transform, which describes the frequency content of signals. Any calculations that are performed on the spectrum produced by the Fourier transform involve complex numbers. The spectrum is composed of complex numbers for each frequency band (the size of the frequency band is equal to the reciprocal of the time step), that are composed of a real part (measured field quantity for that frequency band) and an imaginary part (determined by the phase). See figure A-1 for a conceptual representation of the imaginary component for a single frequency (tone).

How do we use complex numbers? We use complex numbers to determine the amplitude for specified frequency bands when we want to produce a spectrogram, energy spectral density or power spectral density (see Figure 19). We also perform calculations on complex numbers to estimate PM or intensity from sound pressure measurements from a single hydrophone or a hydrophone pair (Figure 5. Finally, we use the complex numbers from the sound pressure spectrum in comparison with the PM spectrum when we calculate the sound source direction for a directogram (a spectrogram coloured by direction of sound propagation).

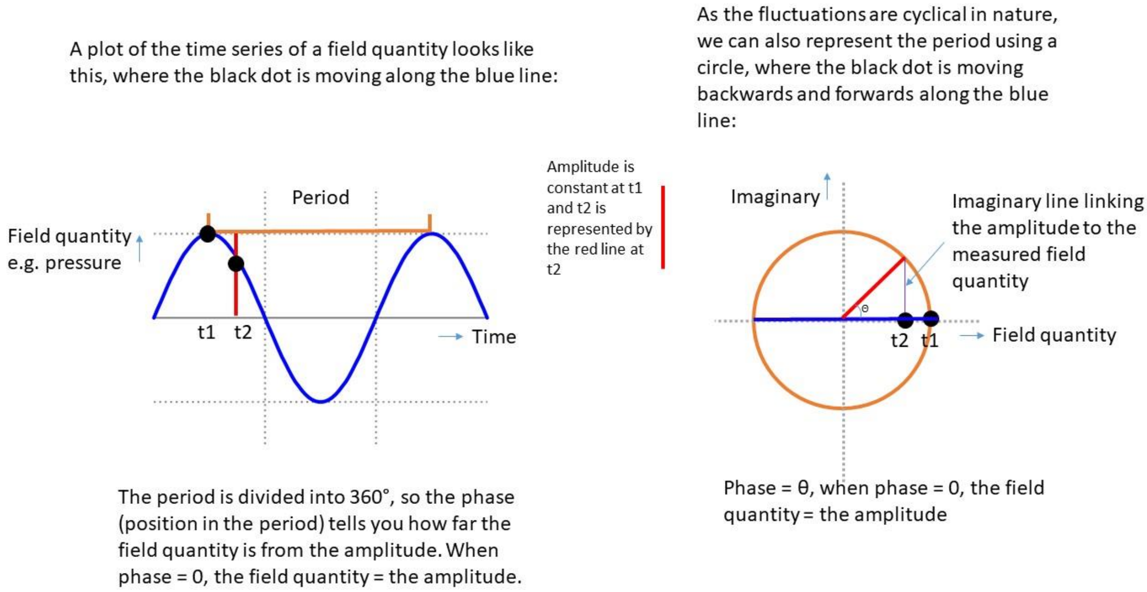

Figure A-1 Schematic representation of the imaginary part of a complex number. Used to describe the link between phase, a measured field quantity and the amplitude of a single frequency (sine or cosine wave).

The left-hand image is the usual sinusoidal representation, which can be represented as

$$x(t) = A\cos(2\pi f t - \phi). \quad \text{Equation 68}$$

We choose to represent this as the real part of the complex variable z(t)

$$z(t) = A\exp\left(2\pi \mathrm{i} f t - \mathrm{i}\phi\right). \quad \text{Equation 69}$$

Here A is the length of the red line, x(t) is the distance of the black dot from the origin at time t, and y(t) is the height of the thin blue line, i.e., the departure from the 'real' axis. The imaginary unit is $\mathrm{i} = \sqrt{-1}$.

A second way to characterise the sound, in Cartesian co-ordinates, is to write

$$z(t) = x(t) + \mathrm{i}y(t). \quad \text{Equation 70}$$

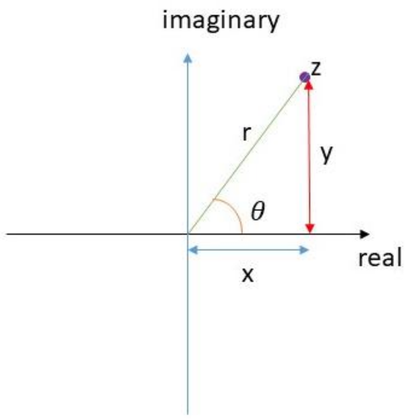

Figure A-2 Representation of a complex number (z) by its real part (x), imaginary part (y), magnitude (r) and phase angle (θ). It follows from standard trigonometry that:

$x = r\, cos\theta$ and $y = r\, sin\theta$, hence, $z = r\, cos\theta + \mathrm{i}\, r\, sin\theta$.

Euler's theorem tells us that:

$$\mathrm{e}^{\mathrm{i}\theta} = \cos\theta + \mathrm{i}\sin\theta \quad \text{Equation 71}$$

Therefore, any complex number can be written as:

$$z = r\, e^{i\theta}$$

The real and imaginary parts of z are indicated by

$$\mathrm{Re}\,[z(t)] = x(t) \quad \text{Equation 72}$$

and

$$\mathrm{Im}\,[z(t)] = y(t), \quad \text{Equation 73}$$

respectively.

When you perform a Fourier transform in MATLAB™ the result is a set of complex numbers represented in Cartesian co-ordinates. On the right-hand side of the schematic in Figure A-1, the triangle formed via the distance of the black dot from the origin on the real (x) axis, the distance of the tip of the red line from the origin on the imaginary (y) and the length of the red line (z) helps us to understand how the amplitude (or the 'magnitude') can be calculated from the complex signal using trigonometry:

$$|z| = \sqrt{x^2 + y^2}. \quad \text{Equation 74}$$

A.6.2 Analytic Signal

A widely used trick to simplify mathematics involves use of complex representation called the analytic signal. Figures A-1 and A-2 show simple representations of a single frequency sine wave or 'pure tone'. For signals with an arbitrary time dependence (i.e., not necessarily a pure tone) analytic signals are used (ISO 18405:2017). The concepts of amplitude and phase are similar but A and ϕ in Equation *68* and Equation *69* become variables instead of constants. Analytic signals are expected to be of interest to some specialist users, for example to calculate sound intensity.

Entries 3.5.1.1-2 define "analytic signal" $q(t)$ and "complex envelope" $\mu(t)$

$$q(t) = p(t) + \mathrm{i}h(t),$$ Equation 75

where $h(t)$ is the Hilbert transform of the sound pressure $p(t)$

$$\mu(t) = q(t)\exp(-2\pi\mathrm{i}\, f_\mathrm{c} t),$$ Equation 76

where f_c is a constant frequency. For a narrowband signal, this frequency is typically the centre frequency of that signal. Field quantities are presented in Table A-5.

Table A-5 Complex representations of field quantities

Term	Definition
A-5.1 analytic sound pressure **symbol**: $q_p(t)$ **Unit**: Pa	quantity equal to $q_p(t) = p(t) + \mathrm{i}h_p(t),$ where $p(t)$ is the sound pressure and $h_p(t)$ is the Hilbert transform of the sound pressure BASED ON: ISO 18405, entry 3.5.1.1 NOTE: The real part of the analytic sound pressure is the sound pressure.
A-5.2 analytic sound particle displacement **symbol**: $\boldsymbol{q}_\delta(t)$ **Unit**: m	quantity equal to $\boldsymbol{q}_\delta(t) = \boldsymbol{\delta}(t) + \mathrm{i}\boldsymbol{h}_\delta(t)$ where $\boldsymbol{\delta}(t)$ is the sound particle displacement and $\boldsymbol{h}_\delta(t)$ is the Hilbert transform of the sound particle displacement BASED ON: ISO 18405:2017, entry 3.5.1.1 NOTE: The real part of the analytic sound particle displacement is the sound particle displacement.
A-5.3 analytic sound particle velocity **symbol**: $\boldsymbol{q}_u(t)$ **Unit**: m s^{-1}	quantity equal to $\boldsymbol{q}_u(t) = \boldsymbol{u}(t) + \mathrm{i}\boldsymbol{h}_u(t),$ where $\boldsymbol{u}(t)$ is the sound particle velocity and $\boldsymbol{h}_u(t)$ is the Hilbert transform of the sound particle velocity BASED ON: ISO 18405:2017, entry 3.5.1.1 NOTE: The real part of the analytic sound particle velocity is the sound particle velocity.

Term	Definition
A-5.4 analytic sound particle acceleration **symbol**: $\boldsymbol{q}_a(t)$ **Unit**: m s^{-2}	quantity equal to $$\boldsymbol{q}_a(t) = \boldsymbol{a}(t) + \mathrm{i}\boldsymbol{h}_a(t),$$ where $\boldsymbol{a}(t)$ is the sound particle acceleration and $\boldsymbol{h}_a(t)$ is the Hilbert transform of the sound particle acceleration BASED ON: ISO 18405:2017, entry 3.5.1.1 NOTE: The real part of the analytic sound particle acceleration is the sound particle acceleration.
A-5.5 complex sound pressure envelope **symbol**: $\mu_p(t)$ **Unit**: Pa	quantity equal to $$\mu_p(t) = q_p(t)\exp(-2\pi\mathrm{i}\, f_\mathrm{c} t),$$ where $q_p(t)$ is the analytic sound pressure, and fc is a constant frequency BASED ON: ISO 18405:2017, entry 3.5.1.2
A-5.6 complex sound particle displacement envelope **symbol**: $\boldsymbol{\mu}_\delta(t)$ **Unit**: m	quantity equal to $$\boldsymbol{\mu}_\delta(t) = \boldsymbol{q}_\delta(t)\exp(-2\pi\mathrm{i}\, f_\mathrm{c} t),$$ where $\boldsymbol{q}_\delta(t)$ is the analytic sound particle displacement, and f_c is a constant frequency BASED ON: ISO 18405:2017, entry 3.5.1.2
A-5.7 complex sound particle velocity envelope **symbol**: $\boldsymbol{\mu}_u(t)$ **Unit**: m s^{-1}	quantity equal to $$\boldsymbol{\mu}_u(t) = \boldsymbol{q}_u(t)\exp(-2\pi\mathrm{i}\, f_\mathrm{c} t),$$ where $\boldsymbol{q}_u(t)$ is the analytic sound particle velocity, and f_c is a constant frequency BASED ON: ISO 18405:2017, entry 3.5.1.2
A-5.8 complex sound particle acceleration envelope **symbol**: $\boldsymbol{\mu}_a(t)$ **Unit**: m s^{-2}	quantity equal to $$\boldsymbol{\mu}_a(t) = \boldsymbol{q}_a(t)\exp(-2\pi\mathrm{i}\, f_\mathrm{c} t),$$ where $\boldsymbol{q}_a(t)$ is the analytic sound particle acceleration, and f_c is a constant frequency BASED ON: ISO 18405:2017 entry 3.5.1.2

A.7 Sound Intensity and Related Quantities

Sound intensity (symbol $\boldsymbol{I}$) is a vector power quantity. Terms and definitions are presented in Table A-6.

Table A-6 Definitions of terms related to sound intensity

Term	Definition
A-6.1 sound intensity **symbol**: $\boldsymbol{I}(t)$ **Unit**: W m^{-2}	product of the sound pressure, p, and the sound particle velocity, $\boldsymbol{u}$ **NOTES**: In equation form $$\boldsymbol{I}(t) = p(t)\boldsymbol{u}(t)$$ where t is time. SOURCE: ISO 18405:2017
A-6.2 time-averaged sound intensity **symbol**: $\boldsymbol{I}_{\mathrm{av}}$ **Unit**: W m^{-2}	integral over a specified time interval (T) of sound intensity, $\boldsymbol{I}$, divided by the duration of the time interval, for a specified frequency range **NOTES**: $$\boldsymbol{I}_{\mathrm{av}} = \frac{1}{T}\int_0^T p(t)\boldsymbol{u}(t)\,\mathrm{d}t$$ SOURCE: ISO 18405:2017
A-6.3 equivalent plane wave intensity **abbreviation**: EPWI **symbol**: I_{eq} **Unit**: W m^{-2}	mean-square sound pressure, $\overline{p^2}$, divided by the product of the density, ρ, and sound speed, c_{w}, of the undisturbed fluid **NOTES**: $$I_{\mathrm{eq}} = \frac{\overline{p^2}}{\rho c_{\mathrm{w}}}$$ SOURCE: ISO 18405:2017

A.8 Particle motion sensitivity

Terms and definitions related to PM sensitivity are presented in Table A-7.

Table A-7 Definitions of terms related to sensitivity.

Term	Definition
A-7.4 sound particle velocity sensitivity **Unit**: V·s/m	ratio of open circuit voltage of a sensor channel to the sound particle velocity at the reference centre of the sensor in the undisturbed free field **NOTES**: The sound particle velocity sensitivity is defined for a specific channel of a particle motion sensor. Typically, a sensor will have three channels corresponding to three orthogonal axes. The sound particle velocity sensitivity is a property of a channel of a particle velocity sensor (e.g., a geophone).
A-7.5 sound particle acceleration sensitivity **Unit**: V·s^2/m	ratio of open circuit voltage of a sensor channel to the sound particle acceleration at the reference centre of the sensor in the undisturbed free field **NOTES**: The sound particle acceleration sensitivity is defined for a specific channel of a particle motion sensor. Typically, a sensor will have three channels corresponding to three orthogonal axes. The sound particle acceleration sensitivity is a property of a channel of a particle acceleration sensor (e.g., an accelerometer).
A-7. 6 pressure gradient sensitivity **Unit**: V·m / Pa	ratio of open circuit voltage of a pressure gradient channel of a particle motion sensor to pressure gradient at the reference centre of the particle motion sensor in the undisturbed free field **NOTES**: The pressure gradient sensitivity is defined for a specific channel of a particle motion sensor. Typically, a sensor will have three channels corresponding to three orthogonal axes. The pressure gradient sensitivity is a property of a channel of a particle motion sensor.

A.9 Level of a Power Quantity

The level, which is on a logarithmic scale, is often used when describing sound due to the large ranges that are commonly used by living organisms. Levels are conventionally expressed in decibels (dB), see Table A-8.

Table A-8 Recommended variable names, abbreviations and symbols: levels of scalar quantities.

Variable Name	Sound Pressure	Displacement	Velocity	Acceleration
power level	mean-square sound pressure level (SPL), L_p $L_p = 10\log_{10}\frac{\overline{p^2}}{p_0^2}\,\mathrm{dB}$	mean-square sound particle displacement level (PDL), L_δ $L_\delta = 10\log_{10}\frac{\overline{\delta^2}}{\delta_0^2}\,\mathrm{dB}$	mean-square sound particle velocity level (PVL), L_u $L_u = 10\log_{10}\frac{\overline{u^2}}{u_0^2}\,\mathrm{dB}$	mean-square sound particle acceleration level (PAL), L_a $L_a = 10\log_{10}\frac{\overline{a^2}}{a_0^2}\,\mathrm{dB}$
energy level	sound pressure exposure level (SEL), $L_{E,p}$ $L_{E,p} = 10\log_{10}\frac{E_p}{p_0^2\, t_0}\,\mathrm{dB}$	sound particle displacement exposure level (PDEL), $L_{E,\delta}$ $L_{E,\delta} = 10\log_{10}\frac{E_\delta}{\delta_0^2\, t_0}\,\mathrm{dB}$	sound particle velocity exposure level (PVEL), $L_{E,u}$ $L_{E,u} = 10\log_{10}\frac{E_u}{u_0^2\, t_0}\,\mathrm{dB}$	sound particle acceleration exposure level (PAEL), $L_{E,a}$ $L_{E,a} = 10\log_{10}\frac{E_a}{a_0^2\, t_0}\,\mathrm{dB}$
power spectral density level (PSDL)	mean-square sound pressure spectral density level, $L_{p,f}$ $L_{p,f} = 10\log_{10}\frac{\overline{p_f^2}}{p_0^2\,/f_0}\,\mathrm{dB}$	mean-square sound particle displacement spectral density level, $L_{\delta,f}$ $L_{\delta,f} = 10\log_{10}\frac{\overline{\delta_f^2}}{\delta_0^2\,/f_0}\,\mathrm{dB}$	mean-square sound particle velocity spectral density level, $L_{u,f}$ $L_{u,f} = 10\log_{10}\frac{\overline{u_f^2}}{u_0^2\,/f_0}\,\mathrm{dB}$	mean-square sound particle acceleration spectral density level, $L_{a,f}$ $L_{a,f} = 10\log_{10}\frac{\overline{a_f^2}}{a_0^2\,/f_0}\,\mathrm{dB}$
energy spectral density level (ESDL)	sound pressure exposure spectral density level, $L_{E,p,f}$ $L_{E,p,f} = 10\log_{10}\frac{E_{p,f}}{p_0^2\, t_0/f_0}\,\mathrm{dB}$	sound particle displacement exposure spectral density level, $L_{E,\delta,f}$ $L_{E,\delta,f} = 10\log_{10}\frac{E_{\delta,f}}{\delta_0^2\, t_0/f_0}\,\mathrm{dB}$	sound particle velocity exposure spectral density level, $L_{E,u,f}$ $L_{E,u,f} = 10\log_{10}\frac{E_{u,f}}{u_0^2\, t_0/f_0}\,\mathrm{dB}$	sound particle acceleration exposure spectral density level, $L_{E,a,f}$ $L_{E,a,f} = 10\log_{10}\frac{E_{a,f}}{a_0^2\, t_0/f_0}\,\mathrm{dB}$

The quantities listed in Table A-8 are all levels of scalar quantities. Analogous quantities can be constructed for the components of a vector (Table A-9).

Table A-9 Recommended variable names and symbols: levels of quantities constructed from component of a vector quantity.

Variable Name	Displacement	Velocity	Acceleration
power level	mean-square sound particle x-displacement level (PDLx), $L_{\delta,x}$	mean-square sound particle x-velocity level (PVLx), $L_{u,x}$	mean-square sound particle x-acceleration level (PALx), $L_{a,x}$
energy level	sound particle x-displacement exposure level (PDELx), $L_{E,\delta,x}$	sound particle x-velocity exposure level (PVELx), $L_{E,u,x}$	sound particle x-acceleration exposure level (PAELx), $L_{E,a,x}$
power spectral density level (PSDL)	mean-square sound particle x-displacement spectral density level, $L_{E,\delta,x}$	mean-square sound particle x-velocity spectral density level, $L_{E,u,x}$	mean-square sound particle x-acceleration spectral density level, $L_{E,a,x}$
energy spectral density level (ESDL)	sound particle x-displacement exposure spectral density level, $L_{E,\delta,x,f}$	sound particle x-velocity exposure spectral density level, $L_{E,u,x,f}$	sound particle x-acceleration exposure spectral density level, $L_{E,a,x,f}$

Examples in the table are for the x component. Symbols for the y or z component are obtained by replacing ‘x’ with ‘y’ or ‘z’ in the obvious way.

SIL is the level of the time-averaged sound intensity,

$$L_I = 10\log_{10}\frac{I_{\mathrm{av}}}{I_0}\ \mathrm{dB}, \quad \text{Equation 77}$$

where I_{av} is the magnitude of the time-averaged intensity vector, and the reference value of sound intensity is

$$I_0 = 1\ \mathrm{pW/m^2}. \quad \text{Equation 78}$$

See Table A-10 for a list of receiver metrics in levels and other logarithmic quantities that are usually expressed in decibels.

Table A-10 Levels and other logarithmic quantities usually expressed in decibels: receiver metrics.

Quantity	Definition
A-10.1 voltage sensitivity level **symbol**: $L_{M,v}$	the quantity $$L_{M,v} = 10 \log \frac{M_{\mathrm{hp},v}^2}{M_{v,0}^2} \text{ dB},$$ where $M_{\mathrm{hp},v}$ is the free-field voltage sensitivity Reference value: $M_{v,0} = 1\ V \ \ /\mu\mathrm{Pa}$ SOURCE: Ainslie et al. (2020)
A-10.2 signal-to-noise level difference **symbol**: ΔL_{SN}	the quantity $$\Delta L_{\mathrm{SN}} = 10 \log R_{\mathrm{SN}} \text{ dB},$$ where R_{SN} is the signal-to-noise power ratio Reference value: NA SOURCE: Ainslie et al. (2020)
A-10.3 hydrophone spectral noise floor level **symbol**: $L_{\mathrm{N,eq},f,\mathrm{hp}}$	level of the hydrophone self-noise spectral density In equation form $$L_{\mathrm{N,eq},f,\mathrm{hp}} = 10 \log \frac{\left(p_{\mathrm{N,eq}}^2\right)_f}{p_0^2/f_0} \text{ dB},$$ where $\left(p_{\mathrm{N,eq}}^2\right)_f$ is the hydrophone self-noise spectral density Reference value: $p_0^2/f_0 = 1\ \mu\mathrm{Pa}^2/\mathrm{Hz}$ SOURCE: Ainslie et al. (2020)
A-10.4 system spectral noise floor level **synonym**: recorder spectral noise floor level **symbol**: $L_{\mathrm{N,eq},f,\mathrm{sys}}$	level of the system self-noise spectral density In equation form $$L_{\mathrm{N,eq},f,\mathrm{sys}} = 10 \log \frac{\left(p_{\mathrm{N,eq}}^2\right)_f}{p_0^2/f_0} \text{ dB},$$ where $\left(p_{\mathrm{N,eq}}^2\right)_f$ is the system self-noise spectral density Reference value: $p_0^2/f_0 = 1\ \mu\mathrm{Pa}^2/\mathrm{Hz}$ SOURCE: Ainslie et al. (2020)
A-10.5 ADC dynamic range **symbol**: $\Delta L_{\mathrm{DR,ADC}}$	the quantity $$\Delta L_{\mathrm{DR,ADC}} = 10 \log \frac{\overline{v_{\mathrm{FS}}^2}}{v_{\mathrm{N,eq,self}}^2} \text{ dB},$$ where $\overline{v_{\mathrm{FS}}^2}$ is the mean-square voltage of a sinusoidal full-scale signal and $v_{\mathrm{N,eq,self}}$ is the equivalent rms ADC self-noise voltage Reference value: NA SOURCE: Ainslie et al. (2020)
A-10.6 system dynamic range **symbol**: $\Delta L_{\mathrm{DR,sys}}$	the quantity $$\Delta L_{\mathrm{DR,sys}} = 10 \log \frac{\overline{v_{\mathrm{FS}}^2}}{v_{\mathrm{N,eq,self}}^2 + \overline{v_{\mathrm{N,self}}^2}} \text{ dB},$$ where $\overline{v_{\mathrm{FS}}^2}$ is the mean-square voltage of a sinusoidal full-scale signal, $v_{\mathrm{N,eq,self}}$ is the equivalent rms ADC self-noise voltage and $v_{\mathrm{N,self}}$ is the non-acoustic self-noise voltage at the ADC input Reference value: NA SOURCE: Ainslie et al. (2020)

Appendix B: Computer Program

B.1 Computer Program for Checking When a Plane Wave Approximation is Not Suitable

You can use the attached decision-making program that applies the rules in Chapter 4 to the recording conditions entered.

Instructions for use of decision-making graphical user interface (GUI):

- Lowest frequency of interest:
  - either lowest frequency that the organism of interest is sensitive to, or
  - the lowest frequency that recording apparatus can record (whichever is higher).
- Highest frequency of interest:
  - highest frequency that the organism of interest is sensitive to, or
  - the highest frequency that recording apparatus can record (whichever is lower)
- Shallowest depth of interest:
  - shallowest depth on the path of propagation of a sound of interest (from source to receiver)
- Distance to source:
  - distance from source to receiver
- Source type:
  - If the source size is much smaller than a wavelength, it can be considered a monopole (Russel et al., 1999)
- Water sound speed:
  - about 1,490 m s^{-1} for seawater at 10 °C
  - about 1,531 m s^{-1} for seawater at 20-25 °C
  - about 1,481 m s^{-1} for fresh water
- Water density:
  - usually 1,027 kg m^{-3} for seawater at 10 °C
  - usually 1,024 kg m^{-3} for seawater at 25 °C
  - usually 1,000 kg m^{-3} for fresh water
- Sediment sound speed: The GUI will calculate this when you click 'calculate' if one of the drop down options for sediment type are chosen.
  - Otherwise enter manually.
    - Sand = 1.1978 * c_w
    - Silt = 1.0479 * c_w

Where c_w = sound speed in water