UNDERWATER ACOUSTICS - TASK 2: PROCESSING

A report prepared by TNO for the Joint Industry Programme on E&P Sound and Marine Life

JIP Topic - Sound source characterisation and propagation

E&P SOUND & MARINE LIFE PROGRAMME

2017

About the E&P Sound & Marine Life Programme

The ocean is filled with a wide variety of natural and man-made sounds. Since the [early 1990s], there has been increasing environmental and regulatory focus on man-made sounds in the sea and on the effects these sounds may have on marine life. There are now many national and international regimes that regulate how we introduce sound to the marine environment. We believe that effective policies and regulations should be firmly rooted in sound independent science. This allows regulators to make consistent and reasonable regulations while also allowing industries that use or introduce sound to develop effective mitigation strategies.

In 2005, a broad group of international oil and gas companies and the International Association of Geophysical Contractors (IAGC) committed to form a Joint Industry Programme under the auspices of the International Association of Oil and Gas Producers (IOGP) to identify and conduct a research programme that improves understanding of the potential impact of exploration and production sound on marine life. The Objectives of the programme were (and remain):

1. To support planning of E&P operations and risk assessments
2. To provide the basis for appropriate operational measures that are protective of marine life
3. To inform policy and regulation.

The members of the JIP are committed to ensuring that wherever possible the results of the studies it commissions are submitted for scrutiny through publication in peer-reviewed journals. The research papers are drawn from data and information in the contract research report series. Both Contract reports and research paper abstracts (and in many cases full papers) are available from the Programme's web site at www.soundandmarinelife.org.

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1 Symbols and abbreviations

Abbreviation	**Stands for**
ADC	analogue to digital converter
BESD	band-averaged energy spectral density
BPSD	band-averaged power spectral density
CSA	Continental Shelf Associates, Inc.
DIS	Draft International Standard
E&P	exploration and production
FESD	Fourier energy spectral density
FPSD	Fourier power spectral density
HF	high-frequency cetaceans
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JIP	E&P Sound and Marine Life Joint Industry Programme
LF	low-frequency cetaceans
MF	mid-frequency cetaceans
NMFS	US National Marine Fisheries Service
NOAA	US National Oceanic and Atmospheric Administration
PK	peak sound pressure level
PW	pinnipeds in water
OP	otariid pinnipeds (in water)
PP	phocid pinnipeds (in water)
SEL	sound exposure level
SEL_{cum}	cumulative sound exposure level
SPL	sound pressure level
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
UA-P	E&P Sound and Marine Life JIP Standard: Underwater Acoustics – Processing (this report)
WBESD	weighted band-averaged energy spectral density
WFESD	weighted Fourier energy spectral density

Symbol	**represents**
unit symbols	
ddec	decidecade
dec	decade
oct	octave
quantity symbols	
E	time-integrated sound field quantity x
E_f	spectral density of E
F	time-integrated sound field quantity y
F_f	spectral density of F
f_m	discrete frequency
J	impulse
P	mean-square value of field quantity x
Q	mean-square value of field quantity y
Q_f	spectral density of Q
t	continuous time
T	continuous time relative to start of time window Δt
t_n	discrete time
$X(t)$	original field quantity
$x(t)$	field quantity in frequency Δf and time window Δt
x_n	discrete representation of $x(t)$
$y(t)$	piecewise constant representation of $x(t)$
Δf	width of frequency band
Δt	duration of time window
τ	duration of transient $x(t)$
υ	duration of transient $y(t)$

2 Introduction

This document is a deliverable of the project ‘Standard Procedures for Underwater Noise Measurements for Activities Related to Offshore Oil and Gas Exploration and Production. Phase I: Processing and Reporting Procedures’ carried out by TNO, in collaboration with CSA and Bioacoustics Consulting, for the Sound and Marine Life Joint Industry Programme (JIP). The objectives of this project are (TNO, 2015):

1) to ensure that the analysis ('acoustical processing') of selected acoustic metrics such as level, duration, and frequency content, used to describe the characteristics of a sound signal propagating in water, can be performed in a consistent and systematic manner;
2) to ensure that the results of such acoustical processing can be reported in such a way that the results reported from two or more studies can be appropriately compared;
3) to define the correspondence between the acoustic metrics to be reported and metrics used in selected previous scientific publications.

The term “acoustical processing” is used here to mean the conversion from time series (e.g., sound pressure vs. time) to processed metrics such as sound pressure level or sound exposure level. This processing is required to provide metrics that are consistent with one another and with the definitions of ISO 18405:2017 (ISO, 2017), and thus facilitate like with like comparison.

The purpose of the project is to standardize the processing and reporting of physical metrics needed by bio-acousticians for assessing the impact of underwater sound on marine life. Standardization of biological studies is outside the project scope.

This document is a standard for processing measurements of underwater sound. It is referred to henceforth as the ‘E&P Sound and Marine Life JIP Standard: Underwater Acoustics – Processing (abbreviated UA-P).

In addition to the present data processing standard (UA-P), JIP standards for terminology (Ainslie et al., 2018) and reporting (Ainslie and de Jong, 2018) are also available. If Phase II of the project is carried out, this will result in the development of JIP standards for measurements of underwater sound.

2.1 Discussion of acoustical processing

The procedure to produce a processed metric begins with an observable ‘field quantity’ which changes with time and is denoted $X(t)$. The variable X may be sound pressure or a directional component of sound particle displacement, particle velocity or particle acceleration. Practical measurements of X require a sensor capable of converting X into a signal that may subsequently be digitized to produce a numerical measure as a function of time. In the case of acoustic pressure, a piezoelectric crystal converts sound pressure to an electrical voltage that is passed through an analogue-to-digital converter (ADC). If the receiver is fully calibrated (i.e., its sensitivity is known precisely), this voltage can be converted back to the value of the sound pressure that caused it, sampled at discrete times, at a rate determined by the characteristics of the ADC. This discretely sampled sound pressure is represented by Xn – a discrete representation of $X(t)$ where n denotes the number of the sample. In order to do this correctly, $X(t)$ is filtered to remove contributions from high frequency sound that the ADC is not able to sample correctly. More specifically, the filter must remove variations in $X(t)$ that occur at frequencies greater than $1/(2\delta t)$ where δt is the time spacing between samples in Xn. If this is not done, the sample is said to be 'aliased' and Xn does not provide a true digitized representation of $X(t)$. It is common for measuring devices to be calibrated only down to a lower frequency limit below which their output can no longer be related to the field quantity of interest. High-pass filters are used to remove signal components below this lower limit and Xn is consequently associated with a frequency band bounded by the lower limit of calibration and the anti-aliasing filter at the upper end. Furthermore, amplifier gains in the recording circuitry must be set so that the input to the ADC never exceeds the value that results in the maximum possible output, set by the number of bits of the ADC. If this maximum is exceeded, the ADC output is 'clipped' and Xn is no longer a true digitized representation of $X(t)$. We have used sound pressure as an example, but for the remainder of this report $X(t)$ is used to represent the instantaneous value of any time-varying field quantity.

It is assumed throughout that a digitized and calibrated signal X_n is available in a known frequency band encompassing all sub-bands of interest, and is free from aliasing and clipping. As such, X_n has an implicit frequency window and dynamic range.

Given the input Xn, two steps must be followed to produce the processed metrics. First, a suitable time window must be selected. This window is a characteristic time over which all metrics are inherently averaged. The data within a time window are nominally copies of values of X_n, with tapering typically applied close to the edge of the window to avoid step changes. Sometimes zeros are used to 'pad' the beginning and end of the window to obtain a convenient number of sample points. Scaling and padding are necessary for the production of processing metrics that involve the use of Fourier transforms while they are not needed for metrics that can be derived more directly from X_n.

In underwater acoustics there is often interest in detecting an acoustic signal in a background of noise. Some of the metrics described in this report distinguish between those describing the signal and those describing the noise. Where relevant, it is assumed in this report that this distinction has been made by identifying time series that are dominated by the signal or contain only noise.
In reality the signal always contains some noise, and strictly speaking a property of the signal is implicitly that of signal plus noise, combined.

2.2 Issues related to measurements

Some details of data acquisition and filtering such as the specifications for anti-alias filter and sampling rate, or the characteristics of frequency and time windows, including tapering and zero padding, are more appropriate for a measurement standard than a data processing standard and are thus outside the present scope.

2.3 Assumptions

This report makes the following assumptions:
a) Discrete time series of sound pressure or sound particle velocity (or other suitable characteristic of particle motion) are available as input to the data processing procedure;
b) these discrete time series are sampled uniformly in time (i.e., for any one time series, the time interval between samples is identical throughout, with no gaps, and no corrupted samples);
c) these discrete time series are calibrated, unsaturated, and filtered for a specified frequency band encompassing all sub-bands of interest
d) these discrete time series are sampled at a rate that comfortable exceeds the Nyquist rate of the continuous signal before digitization (i.e., they are free of aliasing artefacts);

2.4 Outline of this report

Section 3 discusses issues related to the selection of time windows while Section 4 describes processing to produce metrics that do not require the use of a Fourier transform. Section 5 describes processing to produce metrics that require a Fourier transform. Section 6 provides recipes for quantities of interest, including quantities based on sound pressure and on particle motion, as well as levels of both.

2.5 Use of this report

This report is intended to be used as follows. Metrics that might potentially be calculated are listed in a series of tables in Sec. 6. For each metric of interest, the table contains a pointer to the section in the report describing the processing required to obtain the metric, always using the ‘discrete representation’ of the metric in question.

For each discrete representation there is also a description of the ‘continuum representation’ from which the discrete representation is derived. The continuum representation is not an essential part of the recipe and may be ignored without any loss of rigour or precision. The continuum representation is included in the report primarily for those readers wishing to understand the origin of the discrete processing.

3 Selection of frequency and time windows

Prior to detailed calculation of metrics it is necessary to select a frequency sub-band (from f_{min} to f_{max}, bandwith $\Delta f = f_{\mathrm{max}} - f_{\mathrm{min}}$) and time window ($\Delta t$) of interest. Procedures for selecting these quantities follow.

3.1 Selection of sub-band frequency window

A widespread choice of sub-band frequency window is based on one-third octave frequency bands. The international processing standard for one-third octave processing bands is Part 1 of IEC 61260-1:2014 (IEC, 2014); where one-third octave processing is applied, the processing bands prescribed by this IEC standard shall be followed. Frequency bands from IEC (2014) with centre frequencies between 25 Hz and 20 kHz are listed in Table 1. A more complete set of centre frequencies and band-edge frequencies is provided in Table 13 of Ainslie and de Jong (2018).

Table 1 Mid-band frequencies for filters of bandwidth one tenth of a decade (often referred to as “one-third-octave-band” filters) and three tenths of a decade (“octave-band filters”). From IEC (2014).

Index x	Exact f_m in Hz	Exact f_m calculated in Hz	Nominal mid-band frequency in Hz	Octave	One-third-octave
-16	$10^{1,4}$	25,119	25		X
-15	$10^{1,5}$	31,623	31,5	X	X
-14	$10^{1,6}$	39,811	40		X
-13	$10^{1,7}$	50,119	50		X
-12	$10^{1,8}$	63,096	63	X	X
-11	$10^{1,9}$	79,433	80		X
-10	10^{2}	100,00	100		X
-9	$10^{2,1}$	125,89	125	X	X
-8	$10^{2,2}$	158,49	160		X
-7	$10^{2,3}$	199,53	200		X
-6	$10^{2,4}$	251,19	250	X	X
-5	$10^{2,5}$	316,23	315		X
-4	$10^{2,6}$	398,11	400		X
-3	$10^{2,7}$	501,19	500	X	X
-2	$10^{2,8}$	630,96	630		X
-1	$10^{2,9}$	794,33	800		X
0	10^{3}	1 000,0	1 000	X	X
1	$10^{3,1}$	1 258,9	1 250		X
2	$10^{3,2}$	1 584,9	1 600		X
3	$10^{3,3}$	1 995,3	2 000	X	X
4	$10^{3,4}$	2 511,9	2 500		X
5	$10^{3,5}$	3 162,3	3 150		X
6	$10^{3,6}$	3 981,1	4 000	X	X
7	$10^{3,7}$	5 011,9	5 000		X
8	$10^{3,8}$	6 309,6	6 300		X
9	$10^{3,9}$	7 943,3	8 000	X	X
10	10^{4}	10 000	10 000		X
11	$10^{4,1}$	12 589	12 500		X
12	$10^{4,2}$	15 849	16 000	X	X
13	$10^{4,3}$	19 953	20 000		X

NOTE Exact mid-band frequencies were calculated to five significant digits using Formula (2).

The terms “octave-band” and “one-third-octave-band” are used to indicate frequency bands that are approximately one octave and one third of an octave wide. The precise bandwidths of these bands are three tenths of a decade and one tenth of a decade, respectively (IEC, 2014). This apparent discrepancy arises because of a clash between the JIP terminology standard (Ainslie et al. (2018), following ISO (2017)), which defines an octave ratio as a factor of 2 in frequency and the terminology of IEC (2014), which defines an octave ratio as a factor $10^{0.3} \approx 1.9953$ in frequency (see Table 2). The difference in frequency ratio is small, but it can lead to unexpected differences between two nominally identical metrics if one is calculated using the ISO convention for defining “octave” and the other with the IEC convention.

Table 2 Frequency ratios, their relative values, and terminology used to describe them.

Term (Ainslie et al., 2018)	**Definition**	**Value to 5 sig. figs. (* indicates exact value)**	**Notes**
decade **symbol**: dec	decade	1 dec* = 3.3219 oct	n/a
octave **symbol**: oct	octave	0.30103 dec = 1 oct*	IEC (2014) defines the term “octave” to mean three tenths of a decade (0.3 dec = 0.99658 oct)
one-third octave **synonym**: one-third octave (base 2)	one third of an octave	0.10034 dec = 0.33333 oct	n/a
decidecade **synonym**: one-third octave (base 10) **symbol**: ddec	one tenth of a decade	0.1 dec* = 0.33219 oct	IEC (2014) defines the term “one-third-octave” to mean one tenth of a decade

In the remainder of this document, it is assumed that the field quantity $X(t)$ is processed into sub-bands of interest.

3.2 Selection of time window

The calculation of any metric requires as input a number of values of the discretely sampled field quantity ξ_n. These values may cover the whole extent of ξ_n but it is more common that ξ_n is divided into subsets. The selection of these subsets is equivalent to the selection of a time window Δt for the calculation of the metric. The size of the time window may be specified in absolute terms (e.g., a specific number of seconds) or by the properties of the data (e.g., a time containing a proportion of the total energy). The choice of a time window being set to a time containing a certain proportion of energy is commonly used for transient signals.

If the metric is to be calculated by a process that includes a Fourier transform, then there are consequences for the selection of a suitable time window. Many numerical implementations of the Fourier transform require the input signal to have a number of samples that is an integer power of 2. An initial estimate of the time window, $\Delta t'$, based on a particular time period in seconds or on the properties of the data, may not result in a number of samples equal to 2^M where M is an integer. In this case, Δt must be adjusted such that

$$\Delta t = \delta t \; 2^{\mathrm{ceil}[\log_2(\Delta t'/\delta t)]}$$

where ceil$[x]$ denotes the value of x rounded up to the next integer. When this is done, the discrete time-series used to calculate the metric may be made from the subset of ξ_n within time period $\Delta t'$, placed in the centre of the Δt window and with zeros padding the start and end of the window.. When preparing data of this type for input to Fourier transforms, it is usual to 'taper' the data by a 'window' function that avoids 'edge effects' by reducing the amplitude of data at the beginning and end of the window. Many different types of window are available, e.g., Hann, Hamming, Tukey, Nutall (Harris, 1978; Heinzel et al., 2002), each with its strengths and weaknesses. If no Fourier transform is required in the calculation of the metric, the value of Δt used need not be an integer power of 2 and zero padding and windowing are not required. Nevertheless, zero padding can also be used to increase the frequency solution of a Fourier transform by extending the apparent duration of a transient sound. The type and characteristics of the window used and any use of zero-padding should be stated.

When a suitable value of Δt has been chosen it can be used to produce a new representation of the field parameter: x_n. This is the time-windowed version of ξ_n, including any zero-padding or tapering.

3.3 Continuous representation of discretely sampled data

While x_n represents the input data for the calculation of metrics, many of those metrics are defined in terms of continuous functions of time, rather than a series of discrete values. For example, time-integrated measures of total signal energy involve integrals over time and are defined in these terms. To help in the derivation of these metrics, as applied to x_n, two alternative representations of the input data can be introduced.

A continuous version of x_n may be introduced and denoted $x(t)$. This includes any zero-padding and tapering used in the production of x_n but has values for all t, including values that are not equal to integer multiples of δt. Between these integer values, $x(t)$ varies smoothly between x_i and x_{i+1} but it need not necessarily remain within the bounds set by x_i and x_{i+1}. The function $x(t)$ can be thought of as the continuous function reconstructed from x_n using the same frequency spectrum as that determined from x_n but calculated for a continuum of times.

The integral over time of $x(t)$ is not equal to the sum over all x_n multiplied by δt. Since many metrics use integrals, a second continuous function is now introduced, $y(t)$. This, like $x(t)$, is continuous in time but its values are restricted to be members of the set of values contained in x_n. At time t, $y(t)$ has a value equal to the x_n at the nearest value of t_n. The function $y(t)$ is therefore a step-wise 'Manhattan skyline' piecewise constant representation of x_n such that its integral over time is identically equal to the sum over n of x_n multiplied by δt. The situation is shown in Figure 1.

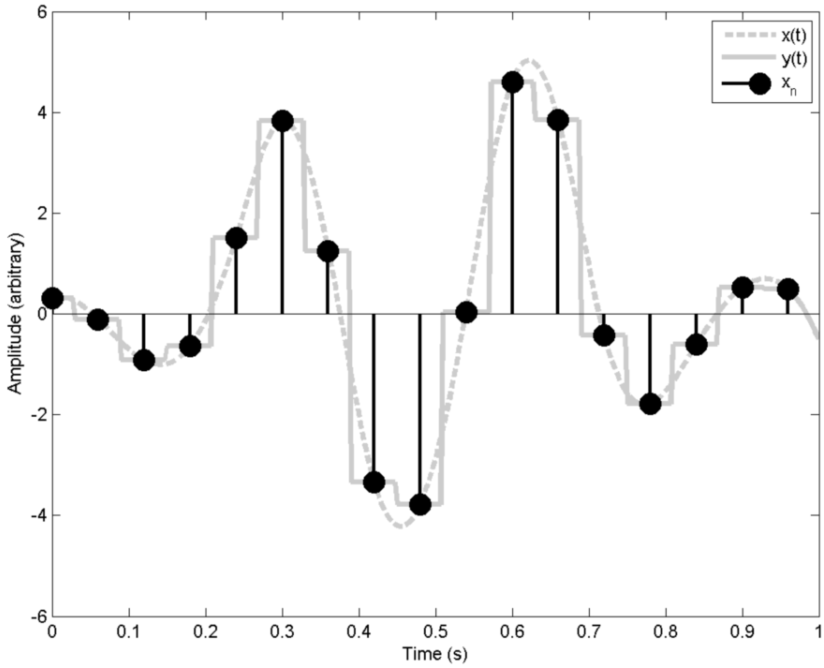


Figure 1 Representation of the digitized signal x_n, with time spacing δt tapered and existing within the time window Δt. Also shown are continuous representations $x(t)$ (which has the same Fourier components) and $y(t)$ (which has approximately the same area under the curve).

The variable $y(t)$ is not intended to correspond to any real signal. It is introduced to facilitate the link between the digital data x_n and integral representations of metrics described in the following sections. The main purpose of introducing $y(t)$ is to help understand the nature of the approximations made by approximating the integral over a continuous function with the corresponding sum over a discretely sampled version of that function. By contrast, $x(t)$ is intended to reproduce the original signal $\xi(t)$ in the frequency band and time window of interest.

4 Metrics not requiring a Fourier transform

The purpose of this section is to specify the calculation of various statistics or metrics from a continuous function of time, $x(t)$, sampled at uniform time intervals δt from t_1 to t_N such that

$$t_n = t_1 + (n-1)\delta t; \;\; n = 1,2,\dots N.$$

The metrics considered in this section are those not requiring a Fourier transform for their evaluation, and for such metrics it is useful to approximate the original continuous function $x(t)$ by the piecewise constant function $y(t)$:

$$y(t) = x(t_n); \quad t_n - \frac{1}{2}\delta t < t \le t_n + \frac{1}{2}\delta t.$$

This piecewise constant representation of $x(t)$ enables one to replace an integral over continuous time by a sum over discrete time, with no further approximation.

We refer to the set of discrete x_n, t_n pairs, where $x_n \equiv x(t_n)$, as the “discrete representation” of $x(t)$.

The continuous function $x(t)$ has duration Δt and is defined between $t_{\mathrm{start}} = t_1 - \frac{1}{2}\delta t$ and $t_{\mathrm{end}} = t_N + \frac{1}{2}\delta t$. Without loss of generality we set the time origin to coincide with t_{start} such that the continuous function is defined between 0 and Δt.

It is assumed that $x(t)$ is a field quantity (ISO, 2006), such as sound pressure. For particle motion the field quantity can also be a component of the sound particle displacement, sound particle velocity, sound particle displacement, or any higher time derivative of the sound particle displacement, all of which are vector quantities; for some metrics the field quantity can be the magnitude of the vector. The field quantity $x(t)$ exists within a frequency band Δf and has a duration Δt.

4.1 Time-integrated squared field quantity

4.1.1 Continuum representation

The time-integrated squared field quantity is defined in terms of the continuous function $x(t)$ as

$$E(\Delta t) \equiv \int_0^{\Delta t} x^2 \,\mathrm{d}t.$$

For example, if the field quantity $x(t)$ is the sound pressure, E is the time-integrated squared sound pressure, or sound pressure exposure.

If $x(t)$ is the magnitude of the sound particle displacement, E is the time-integrated squared sound particle displacement (here referred to as ‘sound particle displacement exposure’).

If $x(t)$ is the magnitude of the sound particle velocity, E is the time-integrated squared sound particle velocity (here referred to as ‘sound particle velocity exposure’).

If $x(t)$ is the magnitude of the sound particle acceleration, E is the time-integrated squared sound particle acceleration (here referred to as 'sound particle acceleration exposure').

4.1.2 *Discrete representation*

In the discrete representation, the time-integrated squared field quantity is

$$E \approx F(\Delta t) \equiv \int_0^{\Delta t} y^2\, \mathrm{d}t = \sum\nolimits_{n=1}^{N} x_n^2 \delta t$$

4.2 Peak field quantity

4.2.1 *Continuum representation*

The peak value of the field quantity is defined as the largest value of its magnitude

$$x_{0\text{-pk}} \equiv \max(|x(t)|);\ 0 < t < \Delta t.$$

4.2.2 *Discrete representation*

Similarly, for the discrete representation

$$y_{0\text{-pk}} \equiv \max(|y(t)|);\ 0 < t < \Delta t$$

and therefore

$$x_{0\text{-pk}} \approx y_{0\text{-pk}} = \max(|x_n|).$$

4.3 Transient duration

4.3.1 *Continuum representation*

ISO (2017) defines three different measures of the duration of an acoustic pulse or transient. These are 2.5.1.3 *effective signal duration*, 2.5.1.4 *threshold exceedance signal duration*, and 2.5.1.5 *percentage energy signal duration*.
Of these, the measure of most relevance to this document is 2.5.1.5 percentage energy signal duration, defined as the *time during which a specified percentage x of time-integrated squared sound pressure occurs*. In the following we adopt the choice $x = 90$, consistent with the requirement of NMFS (2016). The resulting 90 % energy duration, generalized to include particle motion, is referred to henceforth as the "transient duration".

The duration of a transient signal is defined as the time during which 90 % of its "energy" is contained. The "energy" is not the true sound energy but the time-integrated squared field quantity, abbreviated henceforth as "sound exposure". More specifically, the 90 % transient signal duration $\tau_{90\%}$ is the time between $T_{5\%}$ and $T_{95\%}$

$$\tau_{90\%} = T_{95\%} - T_{5\%},$$

where $T_{5\%}$ and $T_{95\%}$ are the times at which 5 % and 95 % of the total sound exposure (E_{tot}) is reached, such that if

$$E(T) = \int_0^T x(t)^2 \,\mathrm{d}t;\ \ 0 < T < \Delta t,$$

then

$$E(T_{5\%}) = 0.05E(\Delta T) = \int_0^{T_{5\%}} x(t)^2 \,\mathrm{d}t$$

and

$$E(T_{95\%}) = 0.95E(\Delta T) = \int_0^{T_{95\%}} x(t)^2 \,\mathrm{d}t.$$

More formally,

$$T_{5\%} = E^{-1}\big(0.05E(\Delta t)\big)$$

and

$$T_{95\%} = E^{-1}\big(0.95E(\Delta t)\big).$$

If the field quantity $x(t)$ is the sound pressure, this recipe gives 90 % energy duration as per entry 2.5.1.5 of ISO (2017) (percentage energy signal duration).

4.3.2 *Discrete representation*

In the discrete representation, the 90 % energy duration $\upsilon_{90\%}$ is the time between $T_{5\%}$ and $T_{95\%}$

$$\upsilon_{90\%} = T_{95\%} - T_{5\%},$$

where $U_{5\%}$ and $U_{95\%}$ are the times at which 5 % and 95 % of the cumulative sound exposure is reached. If F passes through 5 % of total exposure during the time step from $t_{n5} - \frac{1}{2}\delta t$ to $t_{n5} + \frac{1}{2}\delta t$ and through 95 % during the time step from $t_{n95} - \frac{1}{2}\delta t$ to $t_{n95} + \frac{1}{2}\delta t$, the times $T_{5\%}$ and $T_{95\%}$ can be obtained by interpolation using

$$T_{5\%} = t_{n5} - \tfrac{1}{2}\delta t \ + \delta t\ \frac{0.05F(\Delta t) - F\big(t_{n5} - \frac{1}{2}\delta t\big)}{F\big(t_{n5} + \frac{1}{2}\delta t\big) - F\big(t_{n5} - \frac{1}{2}\delta t\big)}$$

$$T_{95\%} = t_{n95} - \tfrac{1}{2}\delta t + \delta t\ \frac{0.95F(\Delta t) - F\big(t_{n95} - \frac{1}{2}\delta t\big)}{F\big(t_{n95} + \frac{1}{2}\delta t\big) - F\big(t_{n95} - \frac{1}{2}\delta t\big)}$$

$$\tau_{90\%} \approx \upsilon_{90\%} = T_{95\%} - T_{5\%}$$

4.4 Mean-square field quantity (full window)

4.4.1 Continuum representation

For a continuous sound, the mean-square value of the field quantity is defined as

$$\overline{x^2} \equiv \frac{1}{\Delta t}\int_0^{\Delta t} x^2 \,\mathrm{d}t.$$

This quantity is related to the time-integrated squared field quantity via

$$\overline{x^2} = \frac{E(\Delta t)}{\Delta t}.$$

4.4.2 Discrete representation

The mean-square value of the discrete representation is

$$\overline{y^2} \equiv \frac{1}{\Delta t}\int_0^{\Delta t} y^2 \,\mathrm{d}t = \frac{1}{N}\sum_{n=1}^{N} x_n^2.$$

Alternatively, this quantity can be calculated from the time-integrated quantity $F(\Delta t)$ via

$$\overline{x^2} \approx \overline{y^2} = \frac{F(\Delta t)}{\Delta t}.$$

4.5 Band-averaged energy spectral density (BESD)

4.5.1 Continuum representation

The energy spectral density can be calculated using a Fourier transform (see Sec.5.1), and the band-averaged energy spectral density (BESD) is then the value of this energy spectral density averaged across a specified frequency band. It is also possible to calculate the BESD without a Fourier transform because of its relation to the time-integrated squared field variable, as expressed by the continuous form of Parseval's theorem (also known as Plancherel's theorem)

$$\int_{-\infty}^{\infty} x(t)^2 \,\mathrm{d}t = \int_{-\infty}^{\infty} |X(f)|^2 \,\mathrm{d}f.$$

Because $x(t)$ has a finite duration Δt, the left-hand side is equal to the time-integrated squared field quantity, $E(\Delta t)$ which is equal to $\overline{x^2}$ multiplied by the duration Δt.

For a signal of finite bandwidth Δf, the BESD is:

$$\overline{E_f} = \frac{E(\Delta t)}{\Delta f}.$$

4.5.2 Discrete representation

For the discrete representation, similar considerations give (for a signal of finite duration Δt and finite bandwidth Δf)

$$\overline{E_f} \approx \overline{F_f} = \frac{F(\Delta t)}{\Delta f}.$$

4.6 Weighted band-averaged energy spectral density (WBESD)

4.6.1 Continuum representation

The weighted sound exposure (E_w) is defined in terms of $p_\mathrm{w}(t)$, which is not defined for (e.g.) M-weighting or NOAA weighting. However, using Plancherel's theorem in the form

$$\int_0^\infty E_{f,\mathrm{w}}(f)\mathrm{d}f = 2\int_0^\infty |P_\mathrm{w}(f)|^2\,\mathrm{d}f$$

it follows that

$$E_{f,\mathrm{w}}(f) = 2|P_\mathrm{w}(f)|^2.$$

The definition of the auditory weighting function $w_\mathrm{aud}(f)$ (ISO, 2017) implies

$$|P_\mathrm{w}(f)|^2 = w_\mathrm{aud}(f)|P(f)|^2,$$

and therefore

$$E_{f,\mathrm{w}}(f) = w_\mathrm{aud}(f)E_f(f).$$

Approximating $E_f(f)$ by its band-averaged value gives

$$E_{f,\mathrm{w}}(f) \approx w_\mathrm{aud}(f)\overline{E_f}$$

$$\overline{E_f} = \frac{1}{\Delta f}\int_{f_\mathrm{min}}^{f_\mathrm{max}} E_f(f)\,\mathrm{d}f$$

and therefore

$$\overline{E_{f,\mathrm{w}}} \approx \overline{w_\mathrm{aud}}\,\overline{E_f},$$

where $\overline{w_\mathrm{aud}}$ is the average value of $w_\mathrm{aud}(f)$ in the frequency band

$$\overline{w_\mathrm{aud}} = \frac{1}{\Delta f}\int_{f_\mathrm{min}}^{f_\mathrm{max}} w_\mathrm{aud}(f)\,\mathrm{d}f$$

If $w_\mathrm{aud}(f)$ can be approximated as a linear function of frequency then

$$\overline{w_\mathrm{aud}} \approx \frac{w_\mathrm{aud}(f_\mathrm{min}) + w_\mathrm{aud}(f_\mathrm{max})}{2}.$$

4.6.2 *Discrete representation*

The same approximations can be applied to the corresponding discrete quantities

$$\overline{E_{f,\mathrm{w}}} \approx \overline{F_{f,\mathrm{w}}} \approx \overline{w_{\mathrm{aud}}}\overline{F_f}.$$

4.7 Band-averaged power spectral density (BPSD)

4.7.1 *Continuum representation*

As with the BESD, the BPSD can be calculated using a Fourier transform (see Sec. 5.3). It is also possible to calculate the BPSD from the BESD by relating it the duration of the signal

$$\overline{P_f} = \frac{(\bar{E})_f}{\Delta \mathrm{t}} = \frac{1}{\Delta \mathrm{t}}\frac{E(\Delta t)}{\Delta f} = \frac{\overline{x^2}}{\Delta f}.$$

4.7.2 *Discrete representation*

For the discrete representation, similar considerations give

$$\overline{P_f} \approx \overline{Q_f} = \frac{(\bar{F})_f}{\Delta \mathrm{t}} = \frac{1}{\Delta \mathrm{t}}\frac{F(\Delta t)}{\Delta f} = \frac{\overline{y^2}}{\Delta f}.$$

4.8 Impulse

4.8.1 *Continuum representation*

The ‘pressure impulse’ is defined (ISO (2017), entry 3.1.5.2) as the integral of a transient sound pressure over time. By analogy, a generalized impulse can be defined for a field quantity $x(t)$ (defined between times 0 and Δt) via

$$J_x = \int_0^{\Delta t} x \,\mathrm{d}t$$

4.8.2 *Discrete representation*

In the discrete representation, the impulse is defined as the integral over the stepwise representation of the field quantity

$$J_y = \int_0^{\Delta t} y \,\mathrm{d}t$$

$$J_x \approx J_y = \delta t \sum_{n=1}^{N} y_n$$

5 Metrics requiring or involving a Fourier transform

The purpose of this section is to specify the calculation of various statistics or metrics from a continuous function of time, $x(t)$, sampled at uniform intervals δt. The metrics considered in this section are of two kinds: those requiring a Fourier transform for their evaluation and those whose calculation from the sampled and time-windowed series x_n might be improved by the use of a Fourier transform.

The Fourier transform is widely used for calculating the spectral density. Metrics involving a spectral density are considered below.

5.1 Fourier energy spectral density (FESD)

A high resolution spectral density can be computed by means of a Fourier transform.

5.1.1 Continuum representation

We begin with the definition of the Fourier transform (ISO, 2009)

$$X(f) = \int_{-\infty}^{+\infty} x(t) \exp(-2\pi \mathrm{i} f t)\, \mathrm{d}t.$$

In Section 4 $x(t)$ was defined as being zero outside the ranges of times between 0 and Δt so that

$$X(f) = \int_{0}^{\Delta t} x(t) \exp(-2\pi \mathrm{i} f t)\, \mathrm{d}t.$$

According to Plancherel's theorem

$$\int_{-\infty}^{+\infty} x^2\, \mathrm{d}t = \int_{-\infty}^{+\infty} |X(f)|^2\, \mathrm{d}f.$$

Since $x(t)$ is a real function, its Fourier transform is symmetric around the zero-frequency and the integral need consider only positive frequencies

$$\int_{0}^{\Delta t} x^2\, \mathrm{d}t = 2\int_{0}^{+\infty} |X(f)|^2\, \mathrm{d}f.$$

So that the Fourier (energy) spectral density at frequency f is

$$E_f(f) = 2|X(f)|^2.$$

5.1.2 Discrete representation

In the discrete representation of the Fourier transform, the frequency content is sought of a discrete series x_n with time sampling $t_n = n\,\delta t$ and a total number of samples $N = \Delta t/\delta t$. The discrete time series yields a discrete series of frequencies, f_m where

$$f_m = \frac{m}{\Delta t} = \frac{m}{N\delta t}\ ; \qquad m = 0, \dots N-1$$

and the discrete Fourier transform of x_n is a complex series X_m, with $X_m = \mathrm{conj}(X_{N-m})$

$$X_m = X(f_m) = \delta t \sum_{n=0}^{N-1} x_n \exp(-\mathrm{i}2\pi nm/N)$$

The multiplication with the sampling interval δt is needed to keep the correct physical units.
Note that in the mathematical sciences this interval is often set to 1.
Note also that most computational implementations of the fast Fourier transform set this interval to 1, so that the user must check whether the outcome needs to be multiplied with δt.

In the time interval Δt, the time series $x(t_n)$ is represented by the inverse transform

$$x(t_n) = \frac{1}{\Delta t} \sum_{m=0}^{N-1} X_m \exp(+\mathrm{i}2\pi nm/N)$$

Under this discrete representation, the Fourier spectral density of x_n becomes.

$$E_f(f_m) \approx F_f(f_m) = 2|X(f_m)|^2$$

5.2 Weighted Fourier energy spectral density (WFESD)

The weighted Fourier energy spectral density is obtained by multiplying the unweighted spectral density by the auditory frequency weighting function, $w_{\mathrm{aud}}(f)$.

5.2.1 Continuum representation

The weighted Fourier energy spectral density is equal to the product of the corresponding unweighted quantity with the auditory frequency weighting function, $w_{\mathrm{aud}}(f)$, i.e.,

$$E_{f,\mathrm{w}}(f) = 2w_{\mathrm{aud}}(f)|X(f)|^2.$$

5.2.2 Discrete representation

In the discrete representation, the weighting is carried out in the same way:

$$E_{f,\mathrm{w}}(f_m) \approx F_{f,\mathrm{w}}(f_m) = 2w_{\mathrm{aud}}(f_m)|X(f_m)|^2.$$

5.3 Fourier power spectral density (FPSD)

5.3.1 Continuum representation

The (time-averaged) FPSD is simply $E_f(f)$ divided by the duration

$$P_f(f) = \frac{E_f(f)}{\Delta t} = \frac{2|X(f)|^2}{\Delta t}$$

5.3.2 Discrete representation

In the discrete representation, this becomes

$$P_f(f_m) \approx Q_f(f_\mathrm{m}) = \frac{2|X(f_m)|^2}{\Delta t}$$

5.4 Band-averaged energy spectral density (BESD)

5.4.1 Continuum representation

The BESD is the average FESD in the frequency band of interest, having width Δf The BESD is thus given by

$$\overline{E_f} = \frac{1}{\Delta f} \int_{f_\mathrm{min}}^{f_\mathrm{max}} 2|X(f)|^2 \ \mathrm{d}f.$$

The bandwidth $\Delta f = f_\mathrm{max} - f_\mathrm{min}$ is the width of the band specified in Section 2. This can be related to mean-square field quantities as set out in section 4.6.

5.4.2 Discrete representation

In the discrete representation, the BESD is the average value of the FESD in the signal band. Since the FESDs are a set of discrete values, taking an average is simple a case of summing the FESD array and dividing by the number of elements

$$\overline{E_f} \approx \overline{F_f} = \frac{1}{N} \sum_{m=1}^{N} 2|X(f_m)|^2$$

5.5 Band-averaged power spectral density (BPSD)

5.5.1 Continuum representation

The BPSD is the BESD divided by the duration of the signal.

$$\overline{P_f} = \frac{\overline{E_f}}{\Delta \mathrm{t}} = \frac{1}{\Delta f \Delta \mathrm{t}} \int_{f_\mathrm{min}}^{f_\mathrm{max}} 2|X(f)|^2 \ \mathrm{d}f.$$

5.5.2 Discrete representation

In the discrete representation, the BPSD is

$$\overline{P_f} \approx \overline{Q_f} = \frac{\overline{F_f}}{\Delta \mathrm{t}} = \frac{1}{N\Delta t}\sum_{m=0}^{N-1} 2|X(f_m)|^2.$$

5.6 Other metrics

The Fourier representation of x_n may be used to recover some metrics (especially the peak value) more accurately than might be achieved directly from x_n itself.

If the sampling interval is sufficient to sample the highest-frequency components at least twice per period, the sampled version, x_n is not aliased but discretization-related concerns remain, particularly in the calculations of metrics related to peak values. The Fourier components of x_n may be used to produce a new time series with a time-sampling that is less than δt. It is likely that this densely sampled time series may have a peak value greater than the maximum value of x_n. This can be visualized by considering a simple sine wave sampled three times each full oscillation. The three samples are enough to determine the amplitude and period of the wave but they do not necessarily include a sample of the wave when it is at its peak value. If the deduced amplitude and period are then used to construct a signal with (say) one hundred times the sampling frequency, the resulting wave will have a maximum value close to the deduced amplitude and consequently higher than any of the original samples. This approach becomes more relevant for values of sampling time that are large relative to the period of the signal.

Improved estimates of peak-related metrics can be obtained by producing a time series $x(t)$, with a sampling frequency exceeding the Nyquist rate by a factor of 10 or more. This densely sampled time series contains the same Fourier components as x_n and the extra temporal resolution allows more accurate determination of peak values.

6 Guidance for calculating specific metrics

In this section we provide a recipe for calculating specific terms of interest. Section 6.1 presents a prescription for the calculation of weighted quantities. This is followed by a description of calculation methods for the cases of single transients (Sec. 6.2), multiple transients (Sec. 6.3) and continuous sounds (Sec. 6.4).

6.1 Evaluation of weighted broadband quantities from WBESD or WFESD

The details for evaluation of weighted broadband quantities depend on whether they are to be calculated from WBESD or WFESD.

6.1.1 Calculation from WBESD

The total weighted broadband sound exposure can be calculated by adding contributions from each sub-band i of width $(\Delta f)_i$, i.e.,

$$E_{\mathrm{w}} = \sum_{i=1}^{M} (\Delta f)_i \left(\overline{F_{f,\mathrm{w}}} \right)_i,$$

where the sum over i runs over all sub-bands of interest, and each frequency band runs from f_{min} to f_{max} such that

$$(\Delta f)_i = (f_{\mathrm{max}})_i - (f_{\mathrm{min}})_i.$$

6.1.2 Calculation from WFESD

Alternatively, if the Fourier spectrum is available, the broadband weighted sound exposure can be summing the individual Fourier components

$$E_{\mathrm{w}} = \delta f \sum_{m=0}^{N-1} \left(F_{f,\mathrm{w}} \right)_m.$$

6.1.3 Example weighting functions

Early auditory weighting functions (“M-weighting”) for marine mammals were introduced in the pioneering work of Southall et al. (2007). These weighting functions are given by

$$w_{\mathrm{aud}}(f) = A_{\mathrm{M}} R_{\mathrm{M}}(f)^2,$$

where

$$R_{\mathrm{M}}(f) = \frac{f_{\mathrm{high}}^2 f^2}{\left(f_{\mathrm{low}}^2 + f^2\right)\left(f_{\mathrm{high}}^2 + f^2\right)}.$$

and A_{M} is defined in such a way that the maximum value of $w_{\mathrm{aud}}(f)$ is unity. In other words

$$A_{\mathrm{M}} = \frac{1}{\max {R_{\mathrm{M}}}^2}.$$

The constants f_{low} and f_{high} are the frequencies below and above which the auditory weighting function deemphasizes contributions relative to those at the flat, central region of the weighting function (see Figure 2), referred to by Southall et al. (2007) as the lower and upper functional hearing limits.

The values specified by Southall et al. (2007) for f_{low}, f_{high} and A_{M} for different marine mammal hearing groups are listed in Table 3, and the resulting weighting curves are plotted in Figure 2 (upper graph).

Table 3 Auditory weighting parameters for Southall et al. (2007) M-weighting (pinnipeds in water, and cetaceans), including estimated lower and upper functional hearing limits.

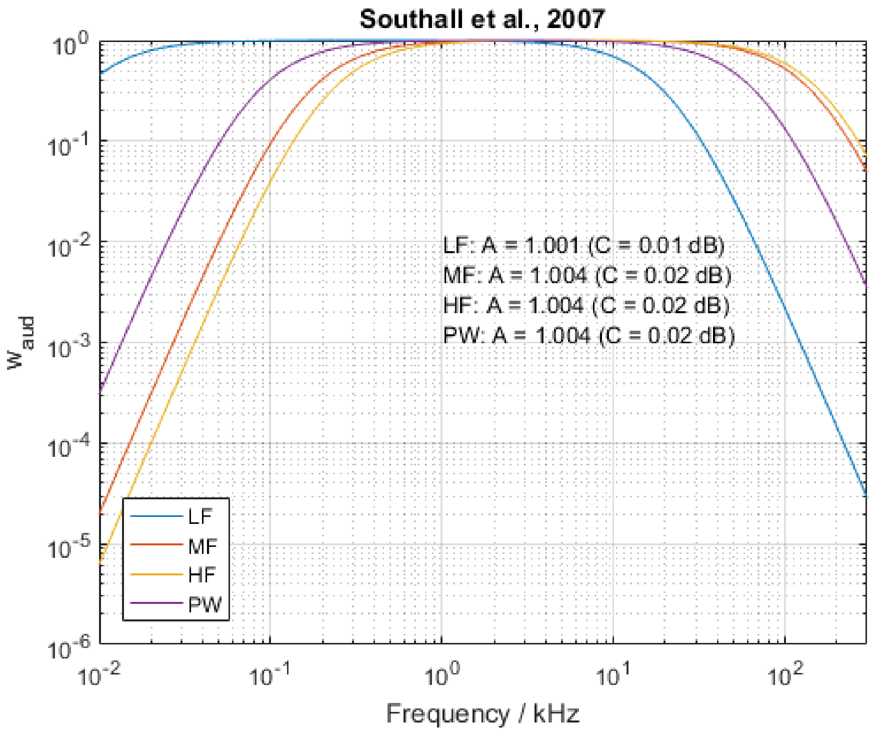
hearing group	$\boldsymbol{a}$	$\boldsymbol{b}$	$\boldsymbol{f}_{\mathbf{low}}$ /kHz	$\boldsymbol{f}_{\mathbf{high}}$ /kHz	$\boldsymbol{C}_{\mathbf{M}}$/dB	$\boldsymbol{A}_{\mathbf{M}}$
low-frequency (LF) cetaceans	2	2	0.007	22	0.01	1.001
mid-frequency (MF) cetaceans	2	2	0.150	160	0.02	1.004
high-frequency (HF) cetaceans	2	2	0.200	180	0.02	1.005
pinnipeds in water (PW)	2	2	0.075	75	0.02	1.004

The constant C_{M} is the logarithm of the factor A_{M}, and may be expressed in decibels:

$$C_{\mathrm{M}} = 10\,\lg A_{\mathrm{M}}\ \ \mathrm{dB}.$$

The numerical value of C_{M} is small because A_{M} is close to unity, which in turn is a consequence of the values of f_{high} being large compared with f_{low} for all hearing groups. The parameters a and b are explained later.

The symbol 'lg' is used to mean '$\log_{10}$', here and throughout this report.



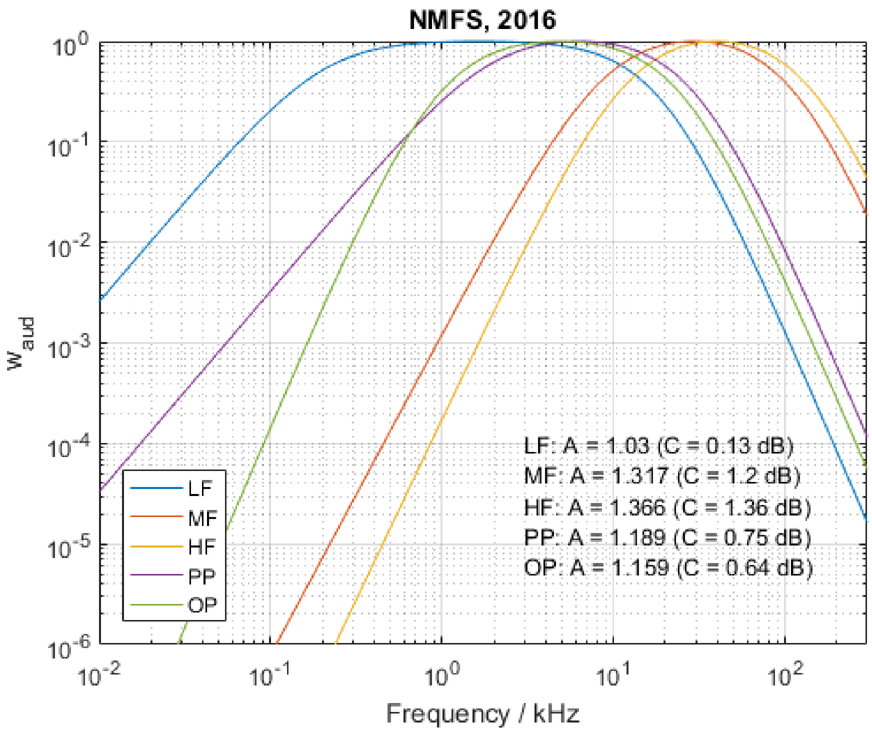


Figure 2 Auditory frequency weighting functions $w_{\mathrm{aud}}(f)$ corresponding to (upper) M-weighting (Southall et al., 2007); and (lower) current NOAA guidance (NMFS, 2016). The abbreviations are explained in Table 3 (or Table 4).

The M-weighting function $M(f)$ defined by Southall et al. (2007) is related to the auditory frequency weighting function $w_{\mathrm{aud}}(f)$ according to

$$M(f) = 10 \lg w_{\mathrm{aud}}(f) \text{ dB},$$

from which it follows that an alternative way of expressing the auditory frequency weighting function, in logarithmic form, is

$$M(f) = C_{\mathrm{M}} + 10 \lg R_{\mathrm{M}}(f)^2 \text{ dB}.$$

This last equation corresponds to Equation 7 from Southall et al. (2007) (p500).

A second important source of guidance on the choice of suitable weighting functions is the NOAA guidance published in July 2016 (NMFS, 2016), describes a generalization of M-weighting of the form

$$w_{\mathrm{aud}}(f) = A_{\mathrm{N}} R_{\mathrm{N}}(f)^2,$$

where

$$R_{\mathrm{N}}(f) = \frac{f_{\mathrm{high}}^b \, f^a}{\left(f_{\mathrm{low}}^2 + f^2\right)^{a/2} \left(f_{\mathrm{high}}^2 + f^2\right)^{b/2}}.$$

As with M-weighting, the constant A_{N} is defined in such a way that the maximum value of $w_{\mathrm{aud}}(f)$ is unity. In other words

$$A_{\mathrm{N}} = \frac{1}{\max R_{\mathrm{N}}{}^2}.$$

The logarithmic weighting function $W(f)$ defined by NMFS (2016), here denoted $N(f)$, is related to the auditory frequency weighting function $w_{\mathrm{aud}}(f)$ according to

$$N(f) = 10 \lg w_{\mathrm{aud}}(f) \text{ dB},$$

from which it follows that

$$N(f) = C_{\mathrm{N}} + 10 \lg R_{\mathrm{N}}(f)^2 \text{ dB},$$

corresponds to Equation 1 from NMFS (2016), p16.

$M(f)$ and $N(f)$ are both examples of the logarithmic auditory frequency weighting function $W_{\mathrm{aud}}(f)$, related to the corresponding linear auditory frequency weighting function $w_{\mathrm{aud}}(f)$ according to

$$W_{\mathrm{aud}}(f) = 10 \lg w_{\mathrm{aud}}(f) \text{ dB},$$

Southall M-weighting is a special case of the NMFS (2016) weighting, with $a = b = 2$. The values of f_{low} and f_{high} (denoted f_1 and f_2 in NMFS (2016); see Table 3) for the NMFS (2016) are repeated here.

The values specified by Southall et al. (2007) for f_{low} , f_{high} and A_{M} for different marine mammal hearing groups are listed in Table 4, and the resulting weighting curves are plotted in Figure 2 (lower graph). The abbreviations “PP” and “OP” are used instead of “PW” and “OW” (from NMFS, 2016) to mean “phocid pinnipeds (underwater)” and “otariid pinnipeds (underwater)”, respectively.

Table 4 Auditory weighting parameters for NMFS (2016) weighting (pinnipeds and otariids in water, and cetaceans), including estimated lower and upper functional hearing limits.

hearing group	a	b	$f_{\mathrm{low}}/\mathrm{kHz}$	$f_{\mathrm{high}}/\mathrm{kHz}$	$C_{\mathrm{N}}/\mathrm{dB}$	A_{N}
low-frequency (LF) cetaceans	1.0	2.0	0.20	19	0.13	1.030
mid-frequency (MF) cetaceans	1.6	2.0	8.80	110	1.20	1.317
high-frequency (HF) cetaceans	1.8	2.0	12.00	140	1.36	1.367
phocid pinnipeds (PP) (underwater)	1.0	2.0	1.90	30	0.75	1.189
otariid pinnipeds (OP) (underwater)	2.0	2.0	0.94	25	0.64	1.159

6.2 Quantities derived from sound pressure or particle motion for a single transient

In the following we present recipes for quantities corresponding to a single transient sound, first for quantities based on sound pressure (Table 5) and then on particle motion (Table 6, Table 7 and Table 8), excluding those that require a Fourier transform. Quantities that require a Fourier transform are included in Table 9. In Table 5 and throughout, the symbol 'lg' is used to indicate a base 10 logarithm ($\log_{10}$). We make no further distinction between discrete and continuous quantities. In all cases, discrete quantities are used to approximate continuous ones.

Table 5 Quantities not requiring a Fourier transform derived from sound pressure for a single transient. Some terms are relevant to the signal and some to the noise (sound without signal). The signal sample duration (Δt_S) should be large enough to contain the entire transient signal and small enough to be uncontaminated by noise (such that the time-integrated squared noise sound pressure is small compared with the signal sound pressure exposure). The noise sample duration (Δt_N) should be approximately equal to the signal sample duration. Both signal and noise sample durations shall be specified. Reference values are $p_0 = 1\ \mu\mathrm{Pa}$ (one micropascal), $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $\boldsymbol{x(t)}$**	**sample duration ($\boldsymbol{\Delta t}$)**	**corresponding level (and common abbreviation)**
band-averaged mean-square noise sound pressure spectral density (BPSD)	$\overline{P_{f,\mathrm{N}}}$	4.7.2 or 5.5.2	noise sound pressure	Δt_N	$10\lg\frac{\overline{P_{f,\mathrm{N}}}}{\frac{p_0^2}{f_0}}$ dB
mean-square noise sound pressure	$\overline{p_\mathrm{N}^2}$	4.4.2	noise sound pressure	Δt_N	$10\lg\frac{\overline{p_\mathrm{N}^2}}{p_0^2}$ dB (SPL)
band-averaged signal sound pressure exposure spectral density (BESD)	$\overline{E_{f,\mathrm{S}}}$	4.5.2 or 5.4.2	signal sound pressure	Δt_S	$10\lg\frac{\overline{E_{f,\mathrm{S}}}}{p_0^2 t_0/f_0}$ dB
signal sound pressure exposure	E_S	4.1.2	signal sound pressure	Δt_S	$10\lg\frac{E_\mathrm{S}}{p_0^2 t_0}$ dB (SELss)[1]
signal sound pressure duration	$\tau_{90\%,p}$	4.3.2	signal sound pressure	Δt_S	n/a
band-averaged mean-square signal sound pressure spectral density (BPSD)	$\overline{P_{f,\mathrm{S}}}$	4.7.2 or 5.5.2	signal sound pressure	Δt_S	$10\lg\frac{\overline{P_{f,\mathrm{S}}}}{\frac{p_0^2}{f_0}}$ dB
mean-square signal sound pressure (full time window)	$\overline{p_\mathrm{S}^2}$	4.4.2	signal sound pressure	Δt_S	$10\lg\frac{\overline{p_\mathrm{S}^2}}{p_0^2}$ dB (SPL)

[1] SELss is always the SEL corresponding to 100 % of the sound exposure in a single transient signal, and not 90 % or some other fraction. If E_{90} is the sound exposure for 90 % of the total transient energy, then SELss is the level of $E_{90}/0.9$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level (and common abbreviation)**
mean-square signal sound pressure (90 % energy time window)	$\overline{p_\mathrm{S}^2}$	4.4.2	signal sound pressure	$\tau_{90\%,p}$	$10\,\mathrm{lg}\dfrac{\overline{p_\mathrm{S}^2}}{p_0^2}$ dB (SPL)
signal pressure impulse	J_p	4.8.2	signal sound pressure	Δt_S	n/a
zero-to-peak signal sound pressure	$p_{0-\mathrm{pk,S}}$	4.2.2	signal sound pressure	Δt_S	$10\,\mathrm{lg}\dfrac{p_{0-\mathrm{pk,S}}^2}{p_0^2}$ dB (PK, $L_{\mathrm{pk,flat}}$)
zero-to-peak signal sound pressure to pulse duration ratio	n/a	$\dfrac{p_{0-\mathrm{pk,S}}}{\tau_{90\%,p}}$	n/a	Δt_S	n/a

The final entry in Table 5 is the peak to duration ratio introduced in the draft NOAA guidelines of July 2015 (NMFS, 2015). This quantity is not required by NMFS (2016) and is unlikely to be of interest for future work. It is included here for completeness, in case there is a need for an ongoing project to be compliant with NMFS (2015).

Table 6 Quantities not requiring a Fourier transform derived from the magnitude of the sound particle displacement for a single transient. Some terms are relevant to the signal and some to the noise (sound without signal). The signal sample duration (Δt_S) should be large enough to contain the entire transient signal and small enough to be uncontaminated by noise). The noise sample duration (Δt_N) should be approximately equal to the signal sample duration. Both signal and noise sample durations shall be specified. Reference values are $\delta_0 = 1$ pm (one picometre), $f_0 = 1$ Hz, $t_0 = 1$ s.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged mean-square noise sound particle displacement spectral density (BPSD)	$\overline{P_{\delta,f,\mathrm{N}}}$	4.7.2	magnitude of noise sound particle displacement	Δt_N	$10\,\mathrm{lg}\dfrac{\overline{P_{\delta,f,\mathrm{N}}}}{\frac{\delta_0^2}{f_0}}$ dB
mean-square noise sound particle displacement	$\overline{\delta_\mathrm{N}^2}$	4.4.2	magnitude of noise sound particle displacement	Δt_N	$10\,\mathrm{lg}\dfrac{\overline{\delta_\mathrm{N}^2}}{\delta_0^2}$ dB
band-averaged signal sound particle displacement exposure spectral density (BESD)	$\overline{E_{\delta,f,\mathrm{S}}}$	4.5.2	magnitude of signal sound particle displacement	Δt_S	$10\,\mathrm{lg}\dfrac{\overline{E_{\delta,f,\mathrm{S}}}}{\delta_0^2 t_0/f_0}$ dB
signal sound particle displacement exposure	$E_{\delta,\mathrm{S}}$	4.1.2	magnitude of signal sound particle displacement	Δt_S	$10\,\mathrm{lg}\dfrac{E_{\delta,\mathrm{S}}}{\delta_0^2 t_0}$ dB
signal sound particle displacement duration	$\tau_{90\%,\delta}$	4.3.2	magnitude of signal sound	Δt_S	n/a

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
			particle displacement		
band -averaged mean-square signal sound particle displacement spectral density (BPSD)	$\overline{P_{\delta,f,\mathrm{S}}}$	4.7.2	magnitude of signal sound particle displacement	Δt_S	$10\lg\frac{\overline{P_{\delta,f,\mathrm{S}}}}{\frac{\delta_0^2}{f_0}}$ dB
mean-square signal sound particle displacement (full time window)	$\overline{\delta_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle displacement	Δt_S	$10\lg\frac{\overline{\delta_\mathrm{S}^2}}{\delta_0^2}$ dB
mean-square signal sound particle displacement (90 % energy time window)	$\overline{\delta_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle displacement	$\tau_{90\%,\delta}$	$10\lg\frac{\overline{\delta_\mathrm{S}^2}}{\delta_0^2}$ dB
zero-to-peak signal sound particle displacement	$\delta_{0-\mathrm{pk,S}}$	4.2.2	magnitude of signal sound particle displacement	Δt_S	$10\lg\frac{\delta_{0-\mathrm{pk,S}}^2}{\delta_0^2}$ dB

Table 7 Quantities not requiring a Fourier transform derived from the magnitude of the sound particle velocity for a single transient. Some terms are relevant to the signal and some to the noise (sound without signal). The signal sample duration (Δt_S) should be large enough to contain the entire transient signal and small enough to be uncontaminated by noise). The noise sample duration (Δt_N) should be approximately equal to the signal sample duration. Both signal and noise sample durations shall be specified. Reference values are $u_0 = 1\ \mathrm{nm/s}$ (one nanometre per second), $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged mean-square noise sound particle velocity spectral density (BPSD)	$\overline{Q_{u,f,\mathrm{N}}}$	4.7.2	magnitude of noise sound particle velocity	Δt_N	$10\lg\frac{\overline{Q_{u,f,\mathrm{N}}}}{\frac{u_0^2}{f_0}}$ dB
mean-square noise sound particle velocity	$\overline{u_\mathrm{N}^2}$	4.4.2	magnitude of noise sound particle velocity	Δt_N	$10\lg\frac{\overline{u_\mathrm{N}^2}}{u_0^2}$ dB
band-averaged signal sound particle velocity exposure spectral density (BESD)	$\overline{E_{f,\mathrm{S}}}$	4.5.2	magnitude of signal sound particle velocity	Δt_S	$10\lg\frac{\overline{E_{f,\mathrm{S}}}}{\frac{u_0^2 t_0}{f_0}}$ dB
signal sound particle velocity exposure	$E_{u,\mathrm{S}}$	4.1.2	magnitude of signal sound particle velocity	Δt_S	$10\lg\frac{E_{u,\mathrm{S}}}{u_0^2 t_0}$ dB
signal sound particle velocity duration	$\tau_{90\%,u}$	4.3.2	magnitude of signal sound	Δt_S	n/a

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
			particle velocity		
band-averaged mean-square signal sound particle velocity spectral density (BPSD)	$\overline{P_{u,f,\mathrm{S}}}$	4.7.2	magnitude of signal sound particle velocity	Δt_S	$10\lg\frac{\overline{P_{u,f,\mathrm{S}}}}{\frac{u_0^2}{f_0}}$ dB
mean-square signal sound particle velocity (full time window)	$\overline{u_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle velocity	Δt_S	$10\lg\frac{\overline{u_\mathrm{S}^2}}{u_0^2}$ dB
mean-square signal sound particle velocity (90 % energy time window)	$\overline{u_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle velocity	$\tau_{90\%,u}$	$10\lg\frac{\overline{u_\mathrm{S}^2}}{u_0^2}$ dB
zero-to-peak signal sound particle velocity	$u_{0-\mathrm{pk,S}}$	4.2.2	magnitude of signal sound particle velocity	Δt_S	$10\lg\frac{u_{0-\mathrm{pk,S}}^2}{u_0^2}$ dB

Table 8 Quantities not requiring a Fourier transform derived from the magnitude of the sound particle acceleration for a single transient. Some terms are relevant to the signal and some to the noise (sound without signal). The signal sample duration (Δt_S) should be large enough to contain the entire transient signal and small enough to be uncontaminated by noise). The noise sample duration (Δt_N) should be approximately equal to the signal sample duration. Both signal and noise sample durations shall be specified. Reference values are $a_0 = 1\ \mu\mathrm{m/s^2}$ (one micrometre per second squared), $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged mean-square noise sound particle acceleration spectral density (BPSD)	$\overline{P_{a,f,\mathrm{N}}}$	4.7.2	magnitude of noise sound particle acceleration	Δt_N	$10\lg\frac{\overline{P_{a,f,\mathrm{N}}}}{\frac{a_0^2}{f_0}}$ dB
mean-square noise sound particle acceleration	$\overline{a_\mathrm{N}^2}$	4.4.2	magnitude of noise sound particle acceleration	Δt_N	$10\lg\frac{\overline{a_\mathrm{N}^2}}{a_0^2}$ dB
band-averaged signal sound particle acceleration exposure spectral density (BESD)	$\overline{E_{a,f,\mathrm{S}}}$	4.5.2	magnitude of signal sound particle acceleration	Δt_S	$10\lg\frac{\overline{E_{a,f,\mathrm{S}}}}{\frac{a_0^2 t_0}{f_0}}$ dB
signal sound particle acceleration exposure	$E_{a,\mathrm{S}}$	4.1.2	magnitude of signal sound particle acceleration	Δt_S	$10\lg\frac{E_{a,\mathrm{S}}}{a_0^2 t_0}$ dB
signal sound particle acceleration duration	$\tau_{90\%,a}$	4.3.2	magnitude of signal sound	Δt_S	n/a

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
			particle acceleration		
band-averaged mean-square signal sound particle acceleration spectral density (BPSD)	$\overline{P_{a,f,\mathrm{S}}}$	4.7.2	magnitude of signal sound particle acceleration	Δt_S	$10\lg\frac{\overline{P_{a,f,\mathrm{S}}}}{\frac{a_0^2}{f_0}}$ dB
mean-square signal sound particle acceleration (full time window)	$\overline{a_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle acceleration	Δt_S	$10\lg\frac{\overline{a_\mathrm{S}^2}}{a_0^2}$ dB
mean-square signal sound particle acceleration (90 % energy time window)	$\overline{a_\mathrm{S}^2}$	4.4.2	magnitude of signal sound particle acceleration	$\tau_{90\%,a}$	$10\lg\frac{\overline{a_\mathrm{S}^2}}{a_0^2}$ dB
zero-to-peak signal sound particle acceleration	$a_{0-\mathrm{pk,S}}$	4.2.2	magnitude of signal sound particle acceleration	Δt_S	$10\lg\frac{a_{0-\mathrm{pk,S}}^2}{a_0^2}$ dB

Table 9 Quantities requiring a Fourier transform for a single transient. Some terms are relevant to the signal and some to the noise (sound without signal). The signal sample duration (Δt_S) should be large enough to contain the entire transient signal and small enough to be uncontaminated by noise). The noise sample duration (Δt_N) should be approximately equal to the signal sample duration. Both signal and noise sample durations shall be specified. Reference values are $p_0 = 1\ \mu\mathrm{Pa}$, $\delta_0 = 1\ \mathrm{pm}$, $u_0 = 1\ \mathrm{nm/s}$, $a_0 = 1\ \mu\mathrm{m/s^2}$, $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
Fourier mean-square noise sound pressure spectral density (FPSD)	$P_{p,f,\mathrm{N}}$	5.3.2	noise sound pressure	Δt_N	$10\lg\frac{P_{p,f,\mathrm{N}}}{\frac{p_0^2}{f_0}}$ dB
Fourier mean-square noise sound particle displacement spectral density (FPSD)	$P_{\delta,f,\mathrm{N}}$	5.3.2	specified component of noise sound particle displacement	Δt_N	$10\lg\frac{P_{\delta,f,\mathrm{N}}}{\frac{\delta_0^2}{f_0}}$ dB
Fourier mean-square noise sound particle velocity spectral density (FPSD)	$P_{u,f,\mathrm{N}}$	5.3.2	specified component of noise sound particle velocity	Δt_N	$10\lg\frac{P_{u,f,\mathrm{N}}}{\frac{u_0^2}{f_0}}$ dB
Fourier mean-square noise sound particle acceleration spectral density (FPSD)	$P_{a,f,\mathrm{N}}$	5.3.2	specified component of noise sound particle acceleration	Δt_N	$10\lg\frac{P_{a,f,\mathrm{N}}}{\frac{a_0^2}{f_0}}$ dB

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
signal Fourier sound pressure exposure spectral density (FESD)	$E_{p,f,\mathrm{S}}$	5.1.2	signal sound pressure	Δt_S	$10\lg\frac{E_{p,f,\mathrm{S}}}{\frac{p_0^2 t_0}{f_0}}$ dB
signal Fourier sound particle displacement exposure spectral density (FESD)	$E_{\delta,f,\mathrm{S}}$	5.1.2	specified component of signal sound particle displacement	Δt_S	$10\lg\frac{E_{\delta,f,\mathrm{S}}}{\frac{\delta_0^2 t_0}{f_0}}$ dB
signal Fourier sound particle velocity exposure spectral density (FESD)	$E_{u,f,\mathrm{S}}$	5.1.2	specified component of signal sound particle velocity	Δt_S	$10\lg\frac{E_{u,f,\mathrm{S}}}{\frac{u_0^2 t_0}{f_0}}$ dB
signal Fourier sound particle acceleration exposure spectral density (FESD)	$E_{a,f,\mathrm{S}}$	5.1.2	specified component of signal sound particle acceleration	Δt_S	$10\lg\frac{E_{a,f,\mathrm{S}}}{\frac{a_0^2 t_0}{f_0}}$ dB
Fourier mean-square signal sound pressure spectral density (FPSD)	$P_{p,f,\mathrm{S}}$	5.3.2	signal sound pressure	Δt_S	$10\lg\frac{P_{p,f,\mathrm{S}}}{\frac{p_0^2}{f_0}}$ dB
Fourier mean-square signal sound particle displacement spectral density (FPSD)	$P_{\delta,f,\mathrm{S}}$	5.3.2	specified component of signal sound particle displacement	Δt_S	$10\lg\frac{P_{\delta,f,\mathrm{S}}}{\frac{\delta_0^2}{f_0}}$ dB
Fourier mean-square signal sound particle velocity spectral density (FPSD)	$P_{u,f,\mathrm{S}}$	5.3.2	specified component of signal sound particle velocity	Δt_S	$10\lg\frac{P_{u,f,\mathrm{S}}}{\frac{u_0^2}{f_0}}$ dB
Fourier mean-square signal sound particle acceleration spectral density (FPSD)	$P_{a,f,\mathrm{S}}$	5.3.2	specified component of signal sound particle acceleration	Δt_S	$10\lg\frac{P_{a,f,\mathrm{S}}}{\frac{a_0^2}{f_0}}$ dB

6.3 Quantities derived from sound pressure or particle motion for multiple transients

Recipes for quantities corresponding to multiple transients are listed in Table 10.

Table 10 Quantities derived from sound pressure and particle motion for multiple transients. The sample duration (Δt) is chosen to encompass multiple transients and shall be specified. Reference values are $p_0 = 1\ \mu\text{Pa}$, $\delta_0 = 1\ \text{pm}$, $u_0 = 1\ \text{nm/s}$, $a_0 = 1\ \mu\text{m/s}^2$, $f_0 = 1\ \text{Hz}$, $t_0 = 1\ \text{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level (and common abbreviation)**
cumulative sound pressure exposure	E_p	4.1.2	sound pressure	Δt	$10 \lg \frac{E_p}{p_0^2 t_0}$ dB (SEL$_{\text{cum}}$)
cumulative sound particle displacement exposure	E_δ	4.1.2	magnitude of sound particle displacement	Δt	$10 \lg \frac{E_\delta}{\delta_0^2 t_0}$ dB
cumulative sound particle velocity exposure	E_u	4.1.2	magnitude of sound particle velocity	Δt	$10 \lg \frac{E_u}{u_0^2 t_0}$ dB
cumulative sound particle acceleration exposure	E_a	4.1.2	magnitude of sound particle acceleration	Δt	$10 \lg \frac{E_a}{a_0^2 t_0}$ dB

6.4 Quantities derived from sound pressure or particle motion for continuous sound

Recipes for quantities corresponding to continuous sound follow, first for sound pressure (Table 11) and then for particle motion (Table 13 and Table 14).

Table 11 Quantities derived from sound pressure for continuous sound. The sample duration (Δt) shall be specified. Reference values are $p_0 = 1\ \mu\text{Pa}$, $f_0 = 1\ \text{Hz}$, $t_0 = 1\ \text{s}$.

quantity	**symbol**	**section**	**Field quantity $x(t)$**	**Sample duration (Δt)**	**corresponding level (and common abbreviation)**
band-averaged sound pressure exposure spectral density (BESD)	$\overline{E_f}$	4.5.2 or 5.4.2	sound pressure	Δt	$10 \lg \frac{\overline{E_f}}{\frac{p_0^2 t_0}{f_0}}$ dB
Fourier sound pressure exposure spectral density (FESD)	E_f	5.1.2	sound pressure	Δt	$10 \lg \frac{E_f}{\frac{p_0^2 t_0}{f_0}}$ dB
sound pressure exposure	E	4.1.2	sound pressure	Δt	$10 \lg \frac{E}{p_0^2 t_0}$ dB

quantity	**symbol**	**secti on**	**Field quantity $x(t)$**	**Sample duration (Δt)**	**corresponding level (and common abbreviation)**
					(SEL)
band-averaged mean-square sound pressure spectral density (BPSD)	$\overline{P_f}$	4.7.2 or 5.5.2	sound pressure	Δt	$10\lg\frac{\overline{P_f}}{\frac{p_0^2}{f_0}}$ dB
Fourier mean-square sound pressure spectral density (FPSD)	P_f	5.3.2	sound pressure	Δt	$10\lg\frac{P_f}{\frac{p_0^2}{f_0}}$ dB
mean-square sound pressure	$\overline{p^2}$	4.4.2	sound pressure	Δt	$10\lg\frac{\overline{p^2}}{p_0^2}$ dB (SPL)

Table 12 Quantities derived from the magnitude of the sound particle displacement for continuous sound. The sample duration (Δt) shall be specified. Reference values are $\delta_0 = 1$ pm, $f_0 = 1$ Hz, $t_0 = 1$ s.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged sound particle displacement exposure spectral density (BESD)	$\overline{E_{\delta,f}}$	4.5.2	magnitude of sound particle displacement	Δt	$10\lg\frac{E_{\delta,f}}{\frac{\delta_0^2 t_0}{f_0}}$ dB
sound particle displacement exposure	E_δ	4.1.2	magnitude of sound particle displacement	Δt	$10\lg\frac{E_\delta}{\delta_0^2 t_0}$ dB
band-averaged mean-square sound particle displacement spectral density (BPSD)	$\overline{P_{\delta,f}}$	4.7.2	magnitude of sound particle displacement	Δt	$10\lg\frac{\overline{P_{\delta,f}}}{\frac{\delta_0^2}{f_0}}$ dB
mean-square sound particle displacement	δ	4.4.2	magnitude of sound particle displacement	Δt	$10\lg\frac{\overline{\delta^2}}{\delta_0^2}$ dB

Table 13 Quantities derived from the magnitude of the sound particle velocity for continuous sound. The sample duration (Δt) shall be specified. Reference values are $u_0 = 1\ \mathrm{nm/s}$, $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged sound particle velocity exposure spectral density (BESD)	$\overline{E_{u,f}}$	4.5.2	magnitude of sound particle velocity	Δt	$10\lg\frac{\overline{E_{u,f}}}{\frac{u_0^2 t_0}{f_0}}\ \mathrm{dB}$
sound particle velocity exposure	E_u	4.1.2	magnitude of sound particle velocity	Δt	$10\lg\frac{E_u}{u_0^2 t_0}\ \mathrm{dB}$
band-averaged mean-square sound particle velocity spectral density (BPSD)	$\overline{P_{u,f}}$	4.7.2	magnitude of sound particle velocity	Δt	$10\lg\frac{\overline{P_{u,f}}}{\frac{u_0^2}{f_0}}\ \mathrm{dB}$
mean-square sound particle velocity	$\overline{u^2}$	4.4.2	magnitude of sound particle velocity	Δt	$10\lg\frac{\overline{u^2}}{u_0^2}\ \mathrm{dB}$

Table 14 Quantities derived from the magnitude of the sound particle acceleration for continuous sound. The sample duration (Δt) shall be specified. Reference values are $a_0 = 1\ \mathrm{pm}$, $f_0 = 1\ \mathrm{Hz}$, $t_0 = 1\ \mathrm{s}$.

quantity	**symbol**	**sec.**	**field quantity $x(t)$**	**sample duration (Δt)**	**corresponding level**
band-averaged sound particle acceleration exposure spectral density (BESD)	$\overline{E_{a,f}}$	4.5.2	magnitude of sound particle acceleration	Δt	$10\lg\frac{\overline{E_{a,f}}}{\frac{a_0^2 t_0}{f_0}}\ \mathrm{dB}$
sound particle acceleration exposure	E_a	4.1.2	magnitude of sound particle acceleration	Δt	$10\lg\frac{E_a}{a_0^2 t_0}\ \mathrm{dB}$
band -averaged mean-square sound particle acceleration spectral density (BPSD)	$\overline{P_{a,f}}$	4.7.2	magnitude of sound particle acceleration	Δt	$10\lg\frac{\overline{P_{a,f}}}{\frac{a_0^2}{f_0}}\ \mathrm{dB}$
mean-square sound particle acceleration	$\overline{a^2}$	4.4.2	magnitude of sound particle acceleration	Δt	$10\lg\frac{\overline{a^2}}{a_0^2}\ \mathrm{dB}$

6.5 Example of zero-to-peak and root-mean square sound pressure

Figure 3 shows a trace of sound pressure versus time for a simulated underwater sound pressure signal. The labels in the axes show the zero-to-peak and root-mean-square sound pressures, and the signal duration, as bounded by the five- and ninety-five-percentile times for the cumulative sound pressure exposure. Levels association with mean-square sound pressure and sound pressure exposure are also shown as text in the figure.

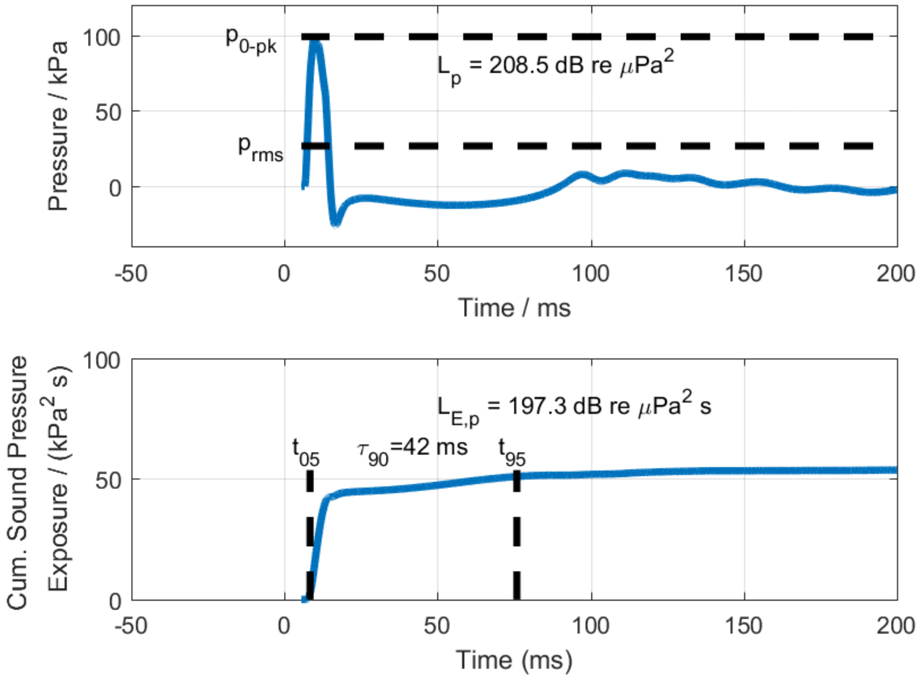


Figure 3 Time-series of pressure (upper panel) and cumulative sound pressure exposure for a simulated underwater sound signal.

The signal shows a strong early peak, followed by lower absolute sound pressure at later times. The duration of the pulse – as defined by τ_{90} – is greater than the duration of the main peak because more than 5 % of the signal's energy lies outside that peak. The peak sound pressure is greater than the mean-square sound pressure in the 90 % energy window, which is shown square-rooted for comparison with the peak.

7 Summary

The analysis of underwater acoustic data makes use of many descriptors and metrics. When data are carefully gathered, avoiding aliasing and clipping and including all necessary calibration and normalization factors it is possible to produce standard measures that agree with ISO standards. These descriptors allow precise comparisons to be made between data from different measurement campaigns using different equipment. Such precise comparisons are necessary if accurate estimates are to be made of any potential impact of sound on aquatic life.

This report has set out definitions of metrics that can be used to describe signal amplitude, frequency-content, duration and energy, and their corresponding levels, where relevant. It has outlined procedures by which these metrics can be calculated, starting from an observable field quantity such as sound pressure, particle displacement, particle velocity or particle acceleration. Although the majority of underwater acoustic measurements available to date are of sound pressure, equal emphasis is given here on particle motion.

8 Acknowledgements

The authors thank Dr. Robert M. Laws (Schlumberger Gould Research Center) and Dr. Roberto Racca (JASCO Applied Sciences) for their thorough and constructive reviews of a draft version of this report. Constructive feedback was also provided by Alex MacGillivray (JASCO Applied Sciences), Roel Müller (TNO), Aran Mooney (Woods Hole Oceanographic Institution), Stephen Robinson and Liansheng Wang (NPL), Michael Jenkerson (Exxon Mobil), Roy Wyatt (Seiche Ltd.) and Stephanie Milne (RPS).

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Contact us

General enquiries

info@soundandmarinelife.org

Media enquiries

press@soundandmarinelife.org
+44 (0) 20 7413 3416

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