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TNO report

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Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units

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Summary

The Netherlands Ministry of Infrastructure and the Environment, Directorate-General for Water Affairs has asked TNO to identify and work with suitable European partners towards the development of standards for the measurement of underwater sound, with a primary focus on acoustic monitoring in relation to the environmental impact of off-shore wind farms. The purpose of this report is to provide an agreed terminology and conceptual definitions for use in the measurement procedures for monitoring of underwater noise, including that associated with wind farm construction. A measurement and reporting procedure for monitoring wind farm construction noise is addressed in a companion report “Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing”.

Samenvatting

In opdracht van het Nederlandse Ministerie van Infrastructuur en Milieu, Directoraat-Generaal Rijkswaterstaat, heeft TNO, samen met een aantal Europese partners, gewerkt aan de totstandkoming van standaarden voor het meten en rapporteren van onderwatergeluid. De primaire focus hierbij was de akoestische monitoring gerelateerd aan mogelijke effecten op het mariene milieu van onderwatergeluid als gevolg van windmolenparken op zee.

Dit rapport bevat de door de partners overeengekomen terminologie en eenduidige, conceptuele definities ten behoeve van de meetprocedures voor het monitoren van onderwatergeluid, waaronder het onderwatergeluid dat gerelateerd is aan de bouw van offshore windmolenparken.

Een procedure voor het meten en rapporteren van onderwatergeluid gerelateerd aan de bouw van windmolenparken komt aan de orde in een begeleidend rapport “Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing”.

Contents

Appendices

1 Introduction

In Europe, initiatives like the Marine Strategy Framework Directive and the OSPAR Convention are aimed at protection of the marine environment. At the same time there is an increased anthropogenic activity in the marine environment.
For example: in March 2009, at the European Wind Energy Conference 2009 (EWEC 2009), the European Wind Energy Association (EWEA) increased its 2020 target to 230 GW wind power capacity, including 40 GW offshore wind [Fichaud & Wilkes 2009].

The Netherlands Ministry of Transport, Public Works and Water Management, Directorate-General for Water Affairs has asked TNO to identify and work with suitable North Sea and European partners towards the development of standards for the measurement and reporting of underwater sound, with a primary focus on acoustic monitoring in relation to the environmental impact of offshore wind farms. The present report has the broader aim of developing an international acoustical terminology standard for underwater noise monitoring generally.

First steps towards reaching international consensus took place during a meeting in December 2009 in The Hague, organised by TNO [de Jong et al 2010]. A second meeting, organised by the UK National Physical Laboratory (NPL), took place in February 2010 in London [Robinson 2011] and a third one, organised by TNO, was held in Delft in February 2011. Participants from Germany, UK and the Netherlands were present at all three meetings. The third meeting was attended by participants from these three nations and also from Belgium, Denmark, Norway, Spain and USA. Discussions took place about common objectives and how to make progress towards these. One conclusion reached during these three meetings was that ambiguity was caused by the lack of precise definitions for some acoustical terms that are central to an adequate description either of the sound pressure field or of sources of sound.

The present TNO project comprises two main tasks, as follows:

- Task 1: *Generic version: standards and definitions of quantities and units related to underwater sound* (this report)
- Task 2: *Specific version: procedures for measuring underwater sound in connection with offshore wind farm licensing* [de Jong et al 2011].

In order to make unambiguous statements about (proposed) measurement standards it is first necessary to establish a precise language. The present purpose is to provide such a language, i.e., to establish an agreed set of definitions of acoustical terms for use in the Task 2 report. Where practical, definitions from existing standards, such as ISO 80000 Part 8: Acoustics of the International Organization for Standardization [ISO 2007], or from Morfey's *Dictionary of Acoustics* [Morfey 2001] are adopted. Where appropriate, use is also made of national standards published by the American National Standards Institute (ANSI).

Wherever practical, SI units and symbols are adopted. Where departures from the SI are necessary, wherever possible units and symbols are adopted from *IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units)* [IEEE 2004].

Essential properties of the definitions adopted are that they be unambiguous and internally consistent. It is further desirable that these definitions follow both existing conventions and existing international standards. In many situations there is no conflict between these *desiderata*, making the choice an easy one. In others, it is necessary to choose between a standard that conflicts with convention and a convention that contravenes one or more international standards. Because of the pressing need for consensus, and because these conflicting situations are the ones for which consensus is likely to be most difficult to achieve, a brief summary of these conflicts is given below, together with a rationale for the choices made.

Examples for which convention has been preferred in the present document over standards are:

- The conventional definition of sound pressure level in terms of a mean square pressure is preferred over the ISO standard [ISO 2007], which defines SPL in terms of the instantaneous sound pressure. There are two reasons for this choice: one is that the ISO standard might be considered impractical because the instantaneous pressure is highly oscillatory; the other is that the instantaneous pressure is not related in a simple way to power, as would be required to maintain consistency with the historical origin of the decibel [Martin 1924, Martin 1929, Horton 1952, Horton 1954, Horton 1959].
- The conventional notation “dB re x_{ref}” is retained even though it is in conflict with IEC and IEEE standards [IEC 2002, IEEE 2004] for use of the decibel alongside SI units, because this notation is in such widespread use that its deprecation would generate unnecessary confusion and defeat the present object.

An example for which an international standard has been preferred over convention is:

- the convention of appending qualifiers to units, for example as subscripts ($\mathrm{dB}_{\mathrm{peak}}$, $\mu\mathrm{Pa}_{\mathrm{RMS}}$) or suffixes (dBSPL) is not followed, because such units are not defined by international standards bodies and generate unnecessary confusion among those unfamiliar with the convention.

An example for which no widely accepted definition exists, and therefore a new definition is needed, is the parameter ‘source level’. This term caused particular difficulties in previous work, reported in [de Jong et al 2010] and [Robinson 2011], and was therefore earmarked for special attention in the present project. At the request of TNO, a meeting took place on 19 May 2010 at the Institute of Sound and Vibration Research (ISVR), University of Southampton, between NPL, ISVR and TNO, with the objective of composing definitions for source level and related quantities. The conclusions of this meeting and subsequent discussions are documented in Appendix B.

The definitions and recommendations contained in this report are proposed by TNO for adoption as a national (Netherlands) standard for reporting numerical values resulting from measurements or predictions of underwater sound. The following organisations agree with the statement “The definitions contained in this document make a suitable starting point from which to construct an international (European) standard”:

- Federal Maritime and Hydrographic Agency of Germany (BSH), Germany;
- TNO Acoustics Department, Netherlands;

- TNO Sonar Department, Netherlands;
- Observation Methodology Group of the Institute of Marine Research, Norway;
- Laboratory of Applied Bioacoustics, Technical University of Catalonia (UPC), Spain;
- National Physical Laboratory, United Kingdom;
- UK Marine Science Coordination Committee Underwater Sound Forum Secretariat, United Kingdom;
- The Underwater Acoustics Group Committee of the Institute of Acoustics, United Kingdom.

Further, participants at the workshop of 3-4 February 2011 were asked to complete a questionnaire that included a question asking whether they agreed with the same statement. Out of 31 participants, 25 completed the questionnaire, all of whom replied to this question in the affirmative, that they agreed with the statement.

In the USA, the need for international standardisation is recognised by the Acoustical Society of America (ASA), as illustrated by the letter from the ASA Standards Director to the Acoustical Oceanography, Animal Bioacoustics and Underwater Acoustics technical committees (Appendix A).

The scope of this report is to provide an agreed terminology and conceptual definitions for use in the measurement procedure. The practical implementation of these definitions is addressed in a companion report [de Jong et al 2011].

The structure of this report is as follows:

- Section 2 introduces the main acoustical terminology needed for the rest of the report.
- Section 3 defines acoustical levels and other quantities expressed in decibels.
- Section 4 describes how the decibel may be used alongside SI units.
- Section 5 defines selected non-SI units and measurement scales of relevance to measurements of underwater sound.
- Section 6 proposes a way ahead for the consolidation and promulgation of this work.
- Appendix A contains a letter by the ASA Standards Director to the Acoustical Oceanography, Animal Bioacoustics and Underwater Acoustics technical committees of the ASA.
- Appendix B proposes definitions for “source level” and related terms.
- Appendix C contains a list of participants at the third international standardisation workshop, held in Delft on 3-4 February 2011.

2 Definitions of acoustical terms

General purpose acoustical terminology, excluding terms expressed in decibels (see Sections 3 and 4) is defined in Table 1. The definitions are presented in alphabetical order.

The following formatting conventions are followed:
- text in **bold** implies a term that is defined in this report;
- text in UPPER CASE implies a term that is defined by [Morfey 2001] and not duplicated in this report;
- a variable symbol in bold implies a vector quantity;
- a variable symbol in italics implies a scalar quantity.

It is convenient to distinguish in some cases between a definition applicable to a continuous signal and one for a transient signal (see for example **unweighted sound exposure**). Further terms for which a definition might be needed, but is not included in Table 1, are listed in Table 2.

Table 1 General acoustical terminology.

term	suggested symbol	definition	notes
acoustic particle velocity		synonym of **sound particle velocity**	
acoustic pressure		synonym of **sound pressure**	
ambient pressure	P_0	synonym of **static pressure**	
auditory critical band		one of a number of contiguous bands of frequency into which the audio-frequency range may be notionally divided, such that sounds in different frequency bands are heard independently of one another, without mutual interference. An auditory critical band can be defined for various measures of sound perception that involve frequency.	[Morfey 2001]
auditory critical bandwidth for loudness for a given centre frequency		the maximum bandwidth over which an acoustic signal can be spread, with its mean square pressure held constant, without affecting the LOUDNESS. Thus the loudness of a continuous sound that lies entirely within a critical bandwidth depends only on the signal level, and not on the bandwidth of the signal. The critical bandwidth for loudness is an increasing function of frequency.	[Morfey 2001]

averaging time	T	the time T in the integral for **RMS sound pressure (1) or RMS sound pressure (3)**	
band-limited signal		imprecise term meaning signal with a well defined bandwidth (2)	
bandwidth (1) of a frequency band between f_{min} (lower limit) and f_{max} (upper limit)	B	the difference between the upper and lower limits of any frequency band. In equation form $B = f_{\mathrm{max}} - f_{\mathrm{min}}$	[Morfey 2001]
bandwidth (2) of a signal		the range of frequencies between lower and upper limits within which most of the energy is contained; see also **half-power bandwidth (2)**, **energy bandwidth (2)** and **signal bandwidth**	[Morfey 2001]
bandwidth (3) of a bandpass filter or transducer		the range of frequencies over which the system is designed to operate	[Morfey 2001]
bandwidth (4) of a bandpass filter		see **filter bandwidth**	[Morfey 2001]
bandwidth (5) of a resonance response curve		see **energy bandwidth (1)**, **half-power bandwidth (1)**	[Morfey 2001]
characteristic impedance	Z	abbreviation for **characteristic specific impedance** of a plane progressive wave.	
characteristic specific impedance of a plane progressive wave	Z	the complex ratio of the pressure to the particle velocity component in the direction of propagation. In a fluid of density ρ and sound speed c, the characteristic impedance is equal to the product $\rho\, c$.	based on [Morfey 2001]
continuous signal in underwater acoustics		synonym of **continuous sound**	
continuous sound		imprecise term meaning a sound for which the mean square **sound pressure** is approximately independent of averaging time	
critical band		in psychoacoustics, abbreviation for **auditory critical band**	[Morfey 2001]
critical bandwidt		see **auditory critical band**, **auditory critical bandwidth for loudness**	[Morfey 2001]
directivity factor of a sound source		the ratio of the far-field **mean square pressure (MSP) (1)** (at a given frequency, in a specified direction from the source) to the average **mean square pressure (MSP) (1)** over a sphere of the same radius, centred on the source. If the source has an axis of symmetry, the directivity factor is understood to refer to	[Morfey 2001]

		the on-axis direction.	
effective bandwidth	v_{eff}	a measure of the frequency bandwidth equal to $\dfrac{\left[\int_0^\infty M(f)^2 \,\mathrm{d}f\right]^2}{\int_0^\infty M(f)^4 \,\mathrm{d}f}$, where *M*(*f*) is the magnitude of the Fourier transform of the analytical function of the signal.	see also [Burdic 1984] and *equivalent statistical bandwidth* [Cavanagh & Laney 2000, p16]
effective time duration of a transient signal	τ_{eff}	the quantity $\dfrac{\left[\int_{-\infty}^{+\infty} p(t)^2 \,\mathrm{d}t\right]^2}{\int_{-\infty}^{+\infty} p(t)^4 \,\mathrm{d}t}$	[Burdic 1984] see also [Cavanagh & Laney 2000, p17] and **sound pressure**
energy bandwidth (1) of a resonant response curve in which the squared gain factor of a linear system is plotted against frequency	B_e	the area under the response curve, normalized by the height of the resonance peak. Mathematically, if the squared gain factor of the system as a function of *frequency* f is *G*(*f*), the energy bandwidth of the system response is $B_e = \dfrac{1}{G_{\max}} \int_0^\infty G(f)\mathrm{d}f$, where $G_{\max}$ is the maximum value of *G*(*f*). The energy bandwidth of a BANDPASS FILTER is referred to as the **equivalent rectangular bandwidth** or **equivalent noise bandwidth** of the filter.	[Morfey 2001]
energy bandwidth (2) of a narrowband signal	B_e	a measure of the frequency bandwidth equal to $B_e = \dfrac{1}{Q_{\max}} \int_0^\infty Q(f)\mathrm{d}f$, where *Q*(*f*) is the **MSP** spectral density of the signal.	based on [Morfey 2001]
energy flux density of a transient signal in underwater acoustics		an equivalent term for the TIME-INTEGRATED INTENSITY at a far-field measurement position.	Based on [Morfey 2001]; see also [Cavanagh & Laney 2000, p12]. See [Morfey 2001] for alternative definition as power per unit area
equivalent noise bandwidth of a		a synonym of **energy bandwidth (1)**	

resonant response curve			
equivalent plane wave intensity (EPWI) of a continuous signal		The intensity of a plane propagating wave with the same **mean square pressure (MSP) (1)** as that of the true signal. If the **characteristic impedance** of the medium is *Z*, the EPWI of the signal is equal to MSP/ *Z*.	[Horton 1959], [Cavanagh & Laney 2000, p8]
equivalent rectangular bandwidth		a synonym of **energy bandwidth (1)**	
equivalent RMS sound pressure of multiple transient signals in a specified frequency band	p_{eq}	synonym of **RMS sound pressure (3)**	
filter bandwidth		Imprecise term for frequency bandwidth within which a BANDPASS FILTER has near-zero INSERTION LOSS. The filter bandwidth may be quoted as an **energy bandwidth (1)**, a **half-power bandwidth (1), effective bandwidth**, or a nominal bandwidth. This last measure is defined as the difference between the upper and lower nominal CUTOFF FREQUENCIES (i.e., the band-edge frequencies).	based on [Morfey 2001]
half-power bandwidth (1) of a resonant response curve in which the squared gain factor of a linear system is plotted against frequency		the frequency separation between the points on either side of the resonance peak where the resonant response curve has fallen to half its peak value	based on [Morfey 2001]
half-power bandwidth (2) of a signal with a peaked power spectrum		the frequency separation between the points on either side of the spectral peak where the **MSP** spectral density has fallen to half its peak value	based on [Morfey 2001]
impulse	**J**	the time integral of a transient force, given by $\mathbf{J} = \int_{-\infty}^{+\infty} \mathbf{F}(t)\mathrm{d}t$ or $\mathbf{J} = \int_{t_1}^{t_2} \mathbf{F}(t)\mathrm{d}t$. Here **F**(*t*) is the force, and the integral is taken either over the entire time-history, or between specified limits (as in the second integral above). The impulse vector represents the total MOMENTUM transferred by the force during that time.	[Morfey 2001]

instantaneous acoustic intensity		synonym of **instantaneous sound intensity**	
instantaneous sound intensity at a point in a time-stationary acoustic field	$\mathbf{I}(t)$	the instantaneous energy flow per unit area at a point in an acoustic field. For sound waves in a stationary medium, it is given by $\mathbf{I}(t) = p(t)\,\mathbf{u}(t)$, where $p(t)$ is the **sound pressure** and $\mathbf{u}(t)$ is the **sound particle velocity** at time t.	from [Morfey 2001, p199]
intermittent sound		imprecise term meaning a sound consisting of one or more similar **transient sounds**	
lower functional hearing limit	f_{low}	lower limit of **M-weighting** frequency filter	see [Southall et al. 2007]
mean square pressure (MSP) (1) of a continuous signal in a specified frequency band	MSP	the quantity $p_{\mathrm{RMS}}{}^2$	see **RMS sound pressure (1)**
mean square pressure (MSP) (2) of a transient signal in a specified frequency band	MSP	the quantity $p_{\mathrm{RMS}}{}^2$	see **RMS sound pressure (2)**
MSP		Abbreviation for **mean square pressure**	
MSP spectral density	$Q(f)$	the contribution to **MSP** per unit of bandwidth	
M-weighting	$W_{\mathrm{M}}(f)$	Frequency weighting function defined by $W_{\mathrm{M}}(f) = \dfrac{S(f)}{\max S(f)}$ where $S(f) = \dfrac{f^4}{(f^2 + f_{\mathrm{high}}^2)^2 (f^2 + f_{\mathrm{low}}^2)^2}$ NOTE: The function $W_{\mathrm{M}}(f)$ is defined here as a linear quantity. It is related to the logarithmic weighting $M(f)$ defined by Southall via the equation $M(f) =$	see [Southall et al. 2007] see **lower functional hearing limit** and **upper functional hearing limit**

		$10\log_{10}W_{\mathrm{M}}(f)$	
negative pressure impulse		for a pulse $p(t)$ satisfying $p(t) \le 0$ over $-T/2 \le t \le T/2$, the quantity $\int_{-T/2}^{+T/2} \lvert p(t)\rvert \mathrm{d}t$	see also **positive pressure impulse**
particle velocity		synonym of **sound particle velocity**	
peak acoustic pressure	$p_{\text{z-p}}$	the quantity $\max(p_{\text{peak,c}}, p_{\text{peak,r}})$ always positive	see **peak compressional pressure** and **peak rarefactional pressure**
peak compressional pressure	$p_{\text{peak,c}}$	the quantity $p_{\max} - P_0$ where $p_{\max}$ is the maximum value of the instantaneous total pressure	see **static pressure**
peak rarefactional pressure	$p_{\text{peak,r}}$	the quantity $P_0 - p_{\min}$ where $p_{\min}$ is the minimum value of the instantaneous total pressure	see **static pressure**
peak to peak sound pressure in a specified frequency band	$p_{\text{p-p}}$	For a **transient signal**, one of two quantities $p_{\text{p-p}} = \max\{p(t)\}_{-T/2}^{T/2} - \min\{p(t)\}_{-T/2}^{T/2}$. or $p_{\text{p-p}} = p_{\text{peak,c}} + p_{\text{peak,r}}$	The **peak-to-peak sound pressure** is used for signals that have a distinctive signature comprising a clear pressure minimum immediately following a clear maximum (or vice-versa), as illustrated by the solid black line in Figure 1. Examples are air-gun pulses and dolphin clicks. The definition is not applicable to pulses that do not exhibit this distinctive signature.
positive pressure impulse		for a pulse $p(t)$ satisfying $p(t) \ge 0$ over $-T/2 \le t \le T/2$,	based on [Cavanagh & Laney 2000,

		the quantity $\int_{-T/2}^{+T/2} p(t)\mathrm{d}t$	p11] “positive impulse”; see also **negative pressure impulse**
pressure impulse	*I* (?)	the time integral of a transient acoustic pressure, given by $I = \int_{-\infty}^{+\infty} p(t)\mathrm{d}t$ or $I = \int_{t_1}^{t_2} p(t)\mathrm{d}t$. Here *p*(*t*) is the **acoustic pressure**, and the integral is taken either over the entire time-history, or between specified limits (as in the second integral above).	see also **impulse**
radiant intensity		radiated power per unit solid angle	
RMS sound pressure (1) of a continuous signal in a specified frequency band	p_{RMS}	For a specified averaging time *T*, the quantity $\sqrt{\frac{1}{T}\int_T p(t)^2 \mathrm{d}t}$	see **sound pressure**
RMS sound pressure (2) of a transient signal in a specified frequency band	p_{RMS}	For a specified time origin and **signal duration** *τ*, the quantity $\sqrt{\frac{1}{\tau}\int_{-\tau/2}^{+\tau/2} p(t)^2 \mathrm{d}t}$.	see **sound pressure**
RMS sound pressure (3) of multiple transient signals in a specified frequency band	p_{RMS}	For averaging time *T*, the quantity $\sqrt{\frac{1}{T}\int_{-T/2}^{+T/2} p(t)^2 \mathrm{d}t}$. The averaging time is understood to be carried out over a large number of individual transients.	see sound pressure
signal bandwidth of a continuous band-limited signal	$\beta_{x\%}$	the frequency band within which a percentage *x* of sound power arrives (e.g., β_{90} is the bandwidth in which 90 % of the power is contained) NOTE: For a transmitted signal, the interpretation of the word “power” in this definition is the obvious one, namely the total radiated power of the signal. In the case of a received signal, it is more appropriate to think of a percentage of the received “intensity” or “mean square pressure”. a different interpretation of “power” is needed for the bandwidth of a received	made unambiguous by starting at 50-*x*/2 % and ending at 50+*x*/2 % of total power. (e.g., for β_{90} this range is from 5 to 95 % of the sound power)

		signal compared with a transmitted one.	
signal duration (1) of a transient signal for a specified averaging time	$\tau_{y\mathrm{dB}}$	the time during which the SPL exceeds a specified threshold *y* decibels below the maximum SPL	based on [Madsen 2005] if there is more than one threshold crossing in each direction, made unambiguous by choosing the time interval between the first crossing with increasing SPL and the last one with decreasing SPL difficult to measure precisely if amplitude varies slowly with time
signal duration (2) of a transient signal	$\tau_{x\%}$	the time during which a specified percentage *x* of **unweighted sound exposure (2)** occurs (e.g., τ_{90} is the time window during which 90 % of the energy arrives)	based on [Madsen 2005][1] made unambiguous by starting at 50-*x*/2 % and ending at 50+*x*/2 % of total energy. (e.g., for τ_{90} this is 5 to 95 %)
sound exposure	*E*	see **weighted sound exposure** and **unweighted sound exposure**	
sound particle acceleration	**a**	the quantity $\mathbf{a}=\frac{\partial \mathbf{v}}{\partial t}$ where **v** is **sound particle velocity** and *t* is time	[ISO 2007, 8-12]
sound particle displacement	**δ**	instantaneous displacement of a particle in a medium from what would be its position in the absence of sound waves	[ISO 2007, 8-10]
sound particle velocity	**v**	the quantity $\mathbf{v}=\frac{\partial \boldsymbol{\delta}}{\partial t}$	[ISO 2007, 8-11]

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[1] an alternative definition multiplies further by 100/x to compensate for the missing energy

		where **δ** is **sound particle displacement** and t is time	
sound pressure	$p(t)$	difference between instantaneous total pressure and **static pressure** $p(t) = P(t) - P_0$	[ISO 2007, 8-9.2]
specific acoustic impedance in a given direction in a single-frequency sound field	z	the complex ratio $z = p/u$, where p is the local acoustic pressure and u is the particle velocity in the specified direction at the same point. The real part of the specific acoustic impedance is the specific acoustic resistance, and the imaginary part is the specific acoustic reactance.	
static pressure	P_0	pressure that would exist in the absence of sound waves	[ISO 2007, 8-9.1]
third octave band		frequency band whose bandwidth is one **third octave (2)** ; see Table 10	this choice, of **third octave (2),** and not **third octave (1)**, ensures that the third octave centre frequencies are spaced by a ratio of $10^{0.1}$ (not $2^{1/3}$), such that ten **third octaves** make precisely one **decade**
time-averaged acoustic intensity		synonym of **time-averaged sound intensity**	
time-averaged sound intensity at a point in a time-stationary acoustic field	**I**	the time-average rate of energy flow per unit area, denoted by the vector **I**. The component of **I** in any direction is the time-average rate of energy flow per unit area normal to that direction. In the absence of mean flow, $\mathbf{I} = \langle p\mathbf{u} \rangle$ where p is the acoustic pressure, **u** is the particle velocity vector, and angle brackets <…> denote a time average. Also known as sound intensity.	from [Morfey 2001]
transient signal in underwater acoustics		synonym of **transient sound**	
transient sound		imprecise term meaning a sound of finite duration for which the sound exposure becomes independent of integration time when the integration time exceeds that duration.	
transient source		a source of sound that produces a **transient signal**	

unweighted sound exposure (1) of a continuous signal	*E*	for a specified time duration *T*, the quantity $E(T) \equiv \int_{-T/2}^{+T/2} p(t)^2\, dt$	see **sound pressure**
unweighted sound exposure (2) of a transient signal	*E*	the quantity $\int_{-\infty}^{\infty} p(t)^2\, \mathrm{d}t$	see **sound pressure**
unweighted sound exposure spectral density of a transient signal	E_f	the contribution to **sound exposure** *E* per unit of bandwidth	
upper functional hearing limit	f_{high}	upper limit of **M-weighting** frequency filter	see [Southall et al. 2007]
weighted MSP of a continuous signal and in a specified frequency band	$\mathrm{MSP_w}$	for a specified frequency band *B*, the quantity $\int_{-B/2}^{+B/2} W(f) Q(f)\, \mathrm{d}f$, where *Q*(*f*) is the **MSP spectral density** of the signal	see **weighting function**
weighted RMS pressure of a continuous signal and in a specified frequency band	p_{w}	the quantity $\sqrt{\mathrm{MSP_w}}$	see **weighted MSP**
weighted sound exposure (1) of a continuous signal	*E*	for a specified time duration *T*, the quantity $E(T) \equiv \int_{-T/2}^{+T/2} p_w(t)^2\, dt$	see **weighted RMS pressure**
weighted sound exposure (2) of a transient signal	*E*	the quantity $\int_{-\infty}^{\infty} p_w(t)^2\, \mathrm{d}t$	see **weighted RMS pressure**
weighting function	*W*(*f*)	Function of frequency used in the definitions of **weighted MSP** and other weighted quantities	see **M-weighting**
zero to peak sound pressure of a transient signal in a specified frequency band	$p_{\mathrm{z\text{-}p}}$	synonym of **peak acoustic pressure**	

Table 2 Other quantities for which a definition might be needed.

term or concept	suggested symbol	definition	notes
ambient noise			
background noise			
duty cycle			
foreground noise			
kurtosis			
peak of analytical signal (or its envelope)			a more robust indicator of impact might be obtained from peaks in the (complex) analytic signal than from peaks in the real pressure signal
rise time			
self noise			

3 Levels and other quantities expressed in decibels

Acoustical levels and other terms expressed in decibels are defined in this section. The definitions in this section are grouped into four categories:

- quantities expressed in decibels, other than source level, quantities related to source level and levels derived from peak sound pressure (Table 3);
- source level and related quantities (Table 4);
- levels derived from peak sound pressure (Table 5);
- other levels, not yet defined (Table 6).

Within each category, the definitions are provided in alphabetical order. The purpose of the suggested notation is to facilitate cross-referencing between definitions. It is in no case intended to be prescriptive.

3.1 Levels and other quantities expressed in decibels, except source level and quantities related to source level

3.1.1 Conventions for expressing levels in decibels

Physical quantities are sometimes expressed as levels in decibels, and this practice is very common in underwater acoustics. The procedure for converting from a physical (power-like) quantity to the level of that quantity is to divide it by a reference value of the physical parameter, take a base-ten logarithm and multiply the result by a factor of 10. For example, consider the mean spectral density Q, averaged over a bandwidth B, and related to the RMS acoustic pressure p_{RMS} according to

$$p_{\mathrm{RMS}}{}^2 = QB \,. \tag{1}$$

Let the reference values for these three parameters be denoted p_{ref} (acoustic pressure), f_{ref} (bandwidth) and $p_{\mathrm{ref}}^2/f_{\mathrm{ref}}$ (spectral density). Dividing both sides of this equation by p_{ref}^2, and using the identity $p_{\mathrm{ref}}^2 = (p_{\mathrm{ref}}^2/f_{\mathrm{ref}})\, f_{\mathrm{ref}}$ in the right hand side gives

$$\frac{p_{\mathrm{RMS}}{}^2}{p_{\mathrm{ref}}{}^2} = \frac{Q}{p_{\mathrm{ref}}{}^2 f_{\mathrm{ref}}{}^{-1}} \frac{B}{f_{\mathrm{ref}}} \,, \tag{2}$$

Taking logs and multiplying by 10, the mean square pressure (MSP), expressed as a level L_{MSP} in decibels, is therefore

$$L_{\mathrm{MSP}} \equiv 10 \log_{10} \frac{p_{\mathrm{RMS}}{}^2}{p_{\mathrm{ref}}{}^2} = 10 \log_{10} \frac{Q}{p_{\mathrm{ref}}{}^2 f_{\mathrm{ref}}{}^{-1}} + 10 \log_{10} \frac{B}{f_{\mathrm{ref}}} \,. \tag{3}$$

With this reasoning, the natural reference values for the levels representing mean square pressure, spectral density and bandwidth are therefore p_{ref}^2, $p_{\mathrm{ref}}^2/f_{\mathrm{ref}}$ and f_{ref}.

Consider a numerical example with p_{RMS} = 1 Pa (one pascal), B = 1 kHz (one kilohertz) and Q = 1 mPa² / Hz (one millipascal squared per hertz). Using standard reference values p_{ref} = 1 μPa and f_{ref} = 1 Hz (from Table 7) the respective levels in decibels are then

level of mean square pressure (SPL) = 120 dB re 1 μPa²
level of spectral density (SSDL) = 90 dB re 1 μPa²/Hz
level of bandwidth (BW) = 30 dB re 1 Hz (4)

An alternative version of (3) is obtained by first taking the square root of (2):

$$\frac{p_{\mathrm{RMS}}}{p_{\mathrm{ref}}} = \frac{\sqrt{Q}}{p_{\mathrm{ref}} f_{\mathrm{ref}}^{-1/2}} \frac{\sqrt{B}}{f_{\mathrm{ref}}^{1/2}} . \tag{5}$$

Taking logs of (5) (and multiplying by 20 instead of 10 because these quantities are proportional to the square root of the power), the resulting equation relating levels in decibels is

$$20\log_{10} \frac{p_{\mathrm{RMS}}}{p_{\mathrm{ref}}} = 20\log_{10} \frac{\sqrt{Q}}{p_{\mathrm{ref}} f_{\mathrm{ref}}^{-1/2}} + 20\log_{10} \frac{\sqrt{B}}{f_{\mathrm{ref}}^{1/2}} , \tag{6}$$

The numerical example then gives, with these reference values

SPL = 120 dB re 1 μPa
SSDL = 90 dB re 1 μPa/Hz$^{1/2}$ (7)
BW = 30 dB re 1 Hz$^{1/2}$

Equations (4), which is based on 10log$_{10}$(mean square pressure), and (7), based on 20log$_{10}$(RMS pressure) are both internally consistent and completely equivalent. Nevertheless it has become conventional to mix them, resulting in combinations such as

SPL = 120 dB re 1 μPa
SSDL = 90 dB re 1 μPa^2/Hz (8)
BW = 30 dB re 1 Hz

This practice of mixing 10log and 20log conventions is widespread, but is potentially confusing to newcomers because without a clear rule the only way to be sure which of the conventions to apply for any given physical quantity is for the convention for that quantity to be known in advance. (By definition, a newcomer would not have this prior knowledge).

3.1.2 *Principles for expressing levels in decibels*

The following three principles are followed:

- state the physical parameter clearly
- state the reference value of that physical parameter
- reference value is always expressed in SI units

3.1.3 *Definitions*

Table 3 defines levels and other quantities relevant to underwater sound and expressed in decibels. Also given (columns 4 and 5) are the values for the reference quantities according to the “10log” and “20log” conventions described above (see also Section 4.3).

Table 3 Quantities expressed in decibels, except source level, quantities related to source level and quantities related to peak pressure.

term	**reference**	**definition**	**ref. quantity (10lg*P*)**	**ref. quantity (20lg*F*)**
absolute threshold for a particular listener presented with a specified acoustic signal	[Morfey 2001]	the minimum level at which the acoustic signal (e.g. a pure tone) is detectable by the listener, in a specified fraction of trials (conventionally 50%). The term implies quiet listening conditions: that is, it represents the irreducible absolute threshold. In the presence of a MASKING sound or noise, the term masked threshold is appropriate.	μPa²	μPa
band level	[Morfey 2001]	the LEVEL of a signal in a specified frequency band.		
beam pattern of an acoustic receiving or transmitting array	[Morfey 2001]	the normalized sensitivity of the array as a function of arrival direction (when functioning as a receiver), or the normalized output sensitivity as a function of radiation direction (when functioning as a transmitter). For a receiving array irradiated by plane waves at a given frequency, *f*, arriving from direction (θ, ϕ) in spherical polar coordinates, the array sensitivity $G(f, \theta, \phi)$ is defined as the ratio of the output voltage magnitude to the input pressure magnitude. The beam pattern in decibels is then given by $B(f,\theta,\phi) = 20\log_{10}\frac{G(f,\theta,\phi)}{G(f,\theta_{\max},\phi_{\max})}$ Here ($\theta_{\max}$, $\phi_{\max}$) is the arrival direction for which *G* is a maximum at the frequency *f*.	1	1
critical ratio for a tonal signal in white noise		The difference between signal SPL and noise spectral density level at which the signal is just heard above the noise	Hz	$\mathrm{Hz}^{1/2}$
equivalent continuous sound pressure level in a specified frequency band		see **weighted sound pressure level (SPLw)**	μPa²	μPa
hearing threshold level in pure-tone audiometry, for a specified	[Morfey 2001]	the threshold of hearing at that frequency, expressed as a HEARING LEVEL in decibels.	μPa²	μPa

method of auditory stimulus presentation at a given frequency				
MSP spectral density level (MSP-SDL)		For a **continuous signal**, the **MSP** spectral density, expressed in decibels $10\log_{10}\frac{Q}{p_{\mathrm{ref}}^{2}/f_{\mathrm{ref}}}$, where $Q(f)$ is the **MSP spectral density** of the signal	$\mu\mathrm{Pa}^2$ / Hz	$\mu\mathrm{Pa}$ / $\mathrm{Hz}^{1/2}$
particle velocity level	[ANSI 1994]	Ten times the logarithm to the base ten of the ratio of the time-mean-square particle velocity of a given sound or vibration to the square of a specified reference particle velocity.	$\mathrm{nm}^2/\mathrm{s}^2$	nm/s
permanent threshold shift (PTS)	[Morfey 2001]	in psychoacoustics, the component of **threshold shift** that shows no recovery with time after the apparent cause has been removed.	1	1
sound exposure level (SEL**)**		see **weighted sound exposure level** and **unweighted sound exposure level**	$\mu\mathrm{Pa}^2$ s	$\mu\mathrm{Pa}\ \mathrm{s}^{1/2}$
sound pressure level (SPL**)** in a specified frequency band; always unweighted		For a **continuous signal**, the **MSP**, expressed in decibels $10\log_{10}\frac{p_{\mathrm{RMS}}^{2}}{p_{\mathrm{ref}}^{2}}$	$\mu\mathrm{Pa}^2$	$\mu\mathrm{Pa}$
temporary threshold shift (TTS)	[Morfey 2001]	in psychoacoustics, the component of **threshold shift** that shows a recovery with the passage of time after the apparent cause has been removed. Recovery usually occurs within a period ranging from seconds to hours.	1	1
third octave level		level of a specified physical parameter P (proportional to power or energy, such as **mean square pressure**), or F(proportional to the square root of a power or energy, such as **RMS pressure**) relative to a reference value of that parameter (P_{ref} or F_{ref}), in a **third octave band**	P_{ref}	F_{ref}
threshold of hearing of a given sound	[Morfey 2001]	An equivalent term for **absolute threshold**. Also known as threshold of audibility. Compare **hearing threshold level**	$\mu\mathrm{Pa}^2$	$\mu\mathrm{Pa}$
threshold shift	[Morfey 2001]	in psychoacoustics, the amount by which the **absolute threshold** for a given listener is increased, for example through noise exposure or ototoxic	1	1

		drug administration. The shift may be either temporary, i.e. showing progressive recovery with time, or permanent.		
unweighted sound exposure level (SEL) in a specified frequency band		For a **transient signal**, the **unweighted sound exposure (2)**, expressed in decibels $10\log_{10}\frac{E}{p_{\mathrm{ref}}{}^{2}t_{\mathrm{ref}}}$	μPa^2 s	μPa s$^{1/2}$
unweighted sound exposure spectral density level in a specified frequency band (always unweighted)		For a **transient signal**, the quantity $10\log_{10}\frac{E_f}{p_{\mathrm{ref}}{}^{2}t_{\mathrm{ref}}/f_{\mathrm{ref}}}$	μPa^2 s / Hz	μPa s$^{1/2}$/ Hz$^{1/2}$
weighted sound exposure level (SEL$_\mathrm{w}$) for a specified weighting function in a specified frequency band		For a **transient signal**, the weighted sound exposure, expressed in decibels $10\log_{10}\frac{\int_{-\infty}^{+\infty}p_{\mathrm{w}}(t)^2\,\mathrm{d}t}{p_{\mathrm{ref}}{}^{2}t_{\mathrm{ref}}}$, where $p_\mathrm{w}(t)$ is the **weighted RMS pressure**.	μPa^2 s	μPa s$^{1/2}$
weighted SPL (SPL$_\mathrm{w}$) for a specified weighting function in a specified frequency band		For a **continuous signal**, the weighted MSP, expressed in decibels $10\log_{10}\frac{\int_{T}p_{\mathrm{w}}(t)^2\,\mathrm{d}t}{p_{\mathrm{ref}}{}^{2}T}$, where $p_\mathrm{w}(t)$ is the **weighted RMS pressure**. NOTE: Compare **equivalent continuous sound pressure level**, defined by to [ISO 1996-1] as a synonym of this term, used by some to indicate a large averaging time (minutes, hours or days)	μPa^2	μPa

3.2 Source level and related quantities

The terms “source level” and “propagation loss” are used in the sonar equation [Urick 1983, Ainslie 2010] to characterise, respectively, the sound power radiated by an underwater sound source (such as a sonar transmitter), and the transfer function from source to receiver. Both are expressed in decibels and together they provide a quantitative description of the sound field at a receiver in the far field of the sound source. The term “transmission loss” is often used as a synonym of “propagation loss”. The latter term is preferred here because of other possible interpretations of “transmission loss” [Morfey 2001].

There are two reasons for treating these terms together, and separately from the other acoustical terminology: first because it is only together that they provide a consistent description of the sound at a given receiver position; second, because in previous related work [de Jong et al 2010], the terminology related to source level (and by implication to propagation loss) was found to lead to particular difficulties, and is expected to require more discussion than most other terms.

3.2.1 *Idealised definition 1 (infinite uniform medium)*

The term “source level”, though not straightforward to define generally, under certain idealised conditions can be related in a simple way to source power. Specifically, under conditions known as “spherical spreading propagation” (in an infinite lossless uniform medium, and in the far field of the source), the mean square pressure ${p_\mathrm{RMS}}^2$ is inversely proportional to distance *r* from the source

$$ {p_\mathrm{RMS}}^2(r) = \frac{S}{r^2} \tag{9} $$

where *S* is a constant, referred to henceforth as the “source factor”. In this idealised situation, this constant is related to the source level by means of the equation

$$ S = 10^{\mathrm{SL}/10} {p_\mathrm{ref}}^2 {r_\mathrm{ref}}^2 , \tag{10} $$

or (rearranging (10))

$$ \mathrm{SL} = 10 \log_{10} \frac{S}{{p_\mathrm{ref}}^2 {r_\mathrm{ref}}^2} . \tag{11} $$

The source level can be related to the power radiated by an omnidirectional source[2] (in the idealised conditions) using:

$$ \frac{W}{4\pi r^2} = \frac{{p_\mathrm{RMS}}^2(r)}{\rho c} , \tag{12} $$

such that the source factor is

$$ S = \frac{\rho c}{4\pi} W , \tag{13} $$

and therefore

$$ \mathrm{SL} = 10 \log_{10} \frac{\rho c W / 4\pi}{{p_\mathrm{ref}}^2 {r_\mathrm{ref}}^2} . \tag{14} $$

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[2] the restriction to an omnidirectional source can be lifted by replacing *W*/4π with the radiant intensity (power per unit solid angle)

It is more conventional to rearrange (9) and substitute the result in (11):

$$\mathrm{SL} = 10\log_{10}\frac{{p_{\mathrm{RMS}}}^2(r)}{{p_{\mathrm{ref}}}^2} + 10\log_{10}\frac{r^2}{{r_{\mathrm{ref}}}^2}, \tag{15}$$

Equations (11) and (15) are equivalent definitions of source level, both valid for the idealised conditions described. Because it is conventional to use the same definitions of r_{ref} in both (11) and (15), that is r_{ref} = 1 m, both definitions lead to the same numerical decibel value, though with a different reference value.

The above idealised description works in practice in deep water, with no absorption and far from boundaries; but not in shallow water, where the sound reflected from the boundaries complicates the simple picture.

3.2.2 *Idealised definition 2 (point source)*

The first idealised definition might be criticised for its limited applicability to an idealised medium. We therefore offer a second idealised definition that is valid for any fluid medium, by idealising the source instead. This is achieved by exploiting the property of a point source that (provided that the acoustic perturbations are linear) the product of RMS acoustic pressure and distance tends to a constant value close to the source. Using (9), it follows that

$$S = \lim_{r\to 0} p_{\mathrm{RMS}}(r)^2 r^2, \tag{16}$$

and therefore

$$\mathrm{SL} = 10\log_{10}\frac{\lim_{r\to 0} p_{\mathrm{RMS}}(r)^2 r^2}{{p_{\mathrm{ref}}}^2 {r_{\mathrm{ref}}}^2}. \tag{17}$$

3.2.3 *Real-world definition*

For a real (finite) source in a real medium, conditions of spherical spreading do not apply in general, so (15) or (17) are not definitions that can be adopted in practice except in very special situations that approximate the respective idealisations that lead to them. To illustrate this point, some simple departures from spherical spreading are considered below. For example, in the presence of absorption (α is a constant absorption coefficient)

$${p_{\mathrm{RMS}}}^2 = S\frac{\exp(-2\alpha r)}{r^2}. \tag{18}$$

Using (11) to define source level, it follows that

$$\mathrm{SL} = 10\log_{10}\frac{{p_{\mathrm{RMS}}}^2}{{p_{\mathrm{ref}}}^2} + 10\log_{10}\frac{r^2}{{r_{\mathrm{ref}}}^2} + (20\log_{10}\mathrm{e})\alpha r. \tag{19}$$

With cylindrical spreading in a waveguide of depth H (θ is a constant angle), the mean square pressure is

$${p_{\mathrm{RMS}}}^2 = S\frac{2\theta}{rH}, \tag{20}$$

and hence

$$\mathrm{SL} = 10\log_{10}\frac{{p_{\mathrm{RMS}}}^2}{{p_{\mathrm{ref}}}^2} + 10\log_{10}\frac{rH/2\theta}{{r_{\mathrm{ref}}}^2}. \tag{21}$$

More generally, the mean square pressure and source factor are related via

$$p_{\mathrm{RMS}}{}^{2} = SF(r), \tag{22}$$

so that a general-purpose definition could be written

$$\mathrm{SL} = 10\log_{10}\frac{p_{\mathrm{RMS}}{}^{2}}{p_{\mathrm{ref}}{}^{2}} + 10\log_{10}\frac{1/F(r)}{r_{\mathrm{ref}}{}^{2}}, \tag{23}$$

where the propagation factor *F*(*r*) is a function of range, with dimensions of reciprocal area and related to the propagation loss PL(*r*) according to

$$\mathrm{PL}(r) = 10\log_{10}\frac{1/F(r)}{r_{\mathrm{ref}}{}^{2}}. \tag{24}$$

While (23) serves as a means of estimating source level (SL) from a measurement of sound pressure level (assuming that propagation loss (PL) is known), it does not serve as a *definition* of SL unless PL is first defined independently.

A general-purpose definition for the source level of a continuous sound source is provided in Table 4. Also defined is the energy source level of a transient sound source. Both definitions are taken from Appendix B. It is valid for both large and small sources, at any frequency (wavelength large or small compared with the size of the source), and for any liquid medium in which the assumptions of linear acoustics apply. For the reasons explained in Appendix B, there are two different versions of each definition. The two versions result in an identical numerical value of the level, but have a different associated reference value.

Table 4 Source level and related quantities (see also Appendix B).

term	symbol	definition	ref. quantity (10lg*P*)	ref. quantity (20lg*F*)
energy source factor	S_E	The quantity $$S_E \equiv r^2 \int p_{\mathrm{FF}}(t,r)^2 \, \mathrm{d}t$$ where $p_{\mathrm{FF}}(t,r)$ = far-field (and free-field) instantaneous acoustic pressure at distance r	N/A	N/A
energy source level (1) for a finite directional transient source (e.g., sonar transducer) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	ESL_1	SEL at a standard reference distance r_{ref} from a point monopole, placed in a lossless uniform medium (of density ρ_0 and sound speed c_0 and extending to infinity in all directions), that produces the same far-field radiant intensity on the transducer axis of the actual source if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium. NOTE: The numerical value of ESL_1 is identical to that of ESL_2.	μPa² s	μPa $\mathrm{s}^{1/2}$
energy source level (2) for a finite directional transient source (e.g., sonar transducer) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	ESL_2	The value of $10\log_{10} \frac{S_E}{p_{\mathrm{ref}}^2 r_{\mathrm{ref}}^2 t_{\mathrm{ref}}}$ that would exist on the transducer axis, where S_E is the **energy source factor**, if the same directional source were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces. NOTE: The numerical value of ESL_2 is identical to that of ESL_1.	μPa² m² s	μPa m $\mathrm{s}^{1/2}$
propagation loss (1)	PL_1	The difference between **source level (1)** and **sound pressure level**. In equation form $\mathrm{PL}_1 = \mathrm{SL}_1 - \mathrm{SPL}$ NOTE: The numerical value of PL_1 is identical to that of PL_2.	1	1
propagation loss (2)	PL_2	The difference between **source level (2)** and **sound pressure level**. In equation form $\mathrm{PL}_2 = \mathrm{SL}_2 - \mathrm{SPL}$ NOTE: The numerical value of PL_2 is	m²	m

		identical to that of PL_1.		
propagation loss (3)	PL_3	The difference between **energy source level (1)** and **sound exposure level**. In equation form $PL_3 = ESL_1 - SEL$ NOTE: The numerical value of PL_3 is identical to that of PL_4.	1	1
propagation loss (4)	PL_4	The difference between **energy source level (2)** and **sound exposure level**. In equation form $PL_4 = ESL_2 - SEL$ NOTE: The numerical value of PL_4 is identical to that of PL_3.	m²	m
source factor	S	The quantity $S \equiv p_{\mathrm{FF}}{}^2(r) r^2$ where $p_{\mathrm{FF}}(r)$ = far-field (and free-field) instantaneous acoustic pressure at distance r	N/A	N/A
source level (1) for a finite directional source (e.g., sonar transducer) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	SL_1	SPL at a standard reference distance r_{ref} from a point monopole, placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, that produces the same far-field radiant intensity on the transducer axis of the actual source if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium. NOTE: The numerical value of SL_1 is identical to that of SL_2.	μPa²	μPa
source level (2) for a finite directional source (e.g., sonar transducer) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	SL_2	The value of $10\log_{10}\frac{S}{p_{\mathrm{ref}}{}^2 r_{\mathrm{ref}}{}^2}$ that would exist on the transducer axis, where S is the **source factor**, if the same directional source were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces. NOTE: The numerical value of SL_2 is identical to that of SL_1.	μPa² m²	μPa m

3.3 Levels derived from peak sound pressure

It is argued by some (e.g., [Carey 2006]) that a level in decibels is always a measure of power. In practice, levels of quantities that are not related in an obvious way to power (e.g., peak pressure) are often quoted in decibels, causing a conflict between the purist ‘power only’ point of view and the more pragmatic approach. The purpose of this section is to acknowledge this conflict explicitly for the case of the peak sound pressure, provide a pragmatic solution to it, and explain how the pragmatic solution can be reconciled with the purist view. It is addressed at those readers who object to the use of decibels for expressing peak pressures. Those who perceive no difficulty with this practice might therefore prefer to skip this section and proceed to the next one.

The definition of the decibel (see Chapter 4 of this report) permits expression of a power, or a quantity closely related to power, on a logarithmic scale. Therefore the use of the decibel as a unit to quantify a physical quantity implies that that quantity is related in a simple way to a power [Mills & Morfey 2005]. Since power is a time-averaged quantity and peak pressure is an instantaneous field quantity[3], the relationship between peak pressure and power is an ambiguous one unless an explicit conversion rule is provided to do so. The absence of a standardised conversion causes ambiguity; the present purpose is to remove the ambiguity by providing a standard conversion. The same problem would arise in attempting to express, for example, the instantaneous intensity in decibels, instead of the time-averaged intensity. The instantaneous intensity is not often used in underwater acoustics, and when it is used it is normally expressed in SI units (watts per square metre), in which case the problem is avoided. But expressing a peak pressure in decibels is very common, which raises the question of what is meant by it.
In principle one could sweep this question under the carpet by asserting that the peak pressure becomes meaningless when expressed as a level (see [Carey 2006]). Alternatively, one can accept that the practice of expressing peak pressure in decibels is widespread and attempt to provide an unambiguous definition for what is intended. The second of these two paths is followed, with the objective of providing a framework for its interpretation.

The key to the conversion is the construction of an equivalent power (or equivalent RMS pressure) that can then be converted to decibels in the usual way. There are many possible ways of doing this, of which two are described below. Both suggestions for equivalent power signals are artificial, as in neither case does the RMS pressure correspond to a physical property of the true wave.

The notation is not intended to be prescriptive and there is no intended implication that one symbol is preferred over another. For example, alternative symbols L_{peak} or L_{pk} may be used for the zero to peak pressure level if these are preferred to $L_{\mathrm{z\text{-}p}}$. The purpose of suggesting symbols is in order to facilitate cross-referencing between definitions.

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[3] The term ‘field quantity’ is used in some standards to mean the square root of a field quantity. This use is deprecated by [ISO 2009], which adopts instead the term ‘root-power quantity’, defined as ‘a quantity, the square of which is proportional to power when it acts on a linear system’. For the present purpose, the terms ‘field quantity’ and ‘root-power quantity’ may be considered interchangeable

3.3.1 *Equivalent sine wave with RMS pressure equal to peak pressure*

When peak pressure is expressed in decibels, it is sometimes referred to as the "peak sound pressure level" (here denoted $L_{\text{z-p}}$). The definition proposed for this term for a transient sound of peak pressure $p_{\text{z-p}}$, is

$$L_{\text{z-p}} = 10\log_{10}\frac{p_{\text{z-p}}^{2}}{p_{\text{ref}}^{2}}. \tag{25}$$

This quantity is numerically equal to the sound pressure level of a continuous sound (for example, a sine wave) whose RMS pressure is

$$p_{\text{RMS1}} = p_{\text{z-p}}. \tag{26}$$

Figure 1 shows a transient pressure waveform (black line) and an equivalent sine wave (red curve) whose RMS pressure satisfies (26). The peak sound pressure level of the black curve is equal to the sound pressure level of the red one.

The term "peak sound pressure level" is ambiguous because it can be interpreted either as peak (sound pressure level) or (peak sound pressure) level. For this reason the unambiguous term "zero to peak sound pressure level" is proposed instead for the quantity $L_{\text{z-p}}$ defined by (25).

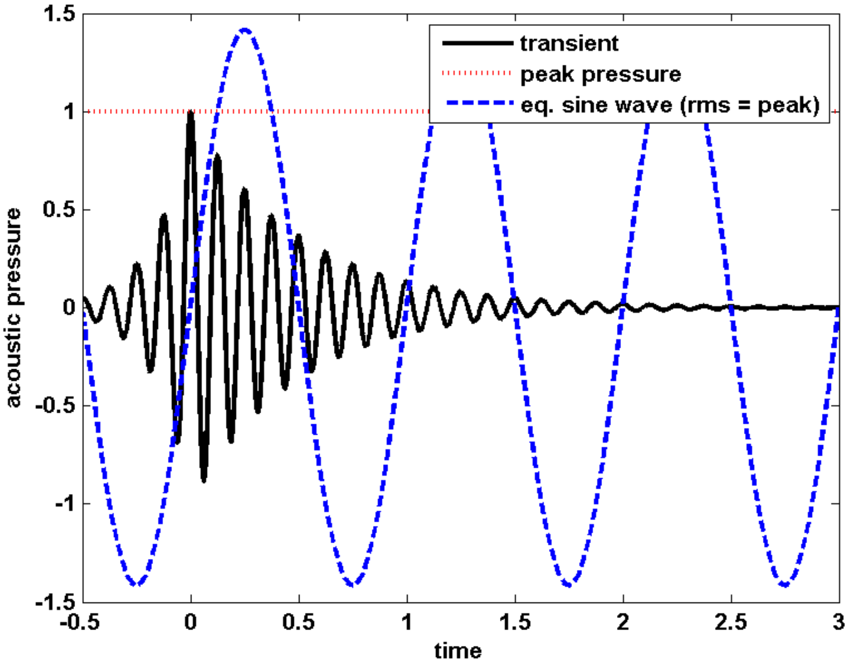

Figure 1 Acoustic pressure of transient (black), peak pressure (red, dotted) and wave form of equivalent sine wave whose rms pressure is equal to the peak pressure of the transient (blue, dashed). The choice in this graph of a lower frequency for the sine wave than the fundamental frequency of the transient is to aid visibility. The RMS pressure of the sine wave is unaffected by this choice.

3.3.2 *Equivalent sine wave with RMS pressure equal to peak to peak pressure*

When peak to peak pressure is expressed in decibels, (here denoted $L_{\text{p-p}}$).

The definition proposed for this term for a transient sound of peak to peak pressure $p_{\text{p-p}}$, is

$$L_{\text{p-p}} = 10 \log_{10} \frac{p_{\text{p-p}}^2}{p_{\text{ref}}^2} . \qquad (27)$$

This quantity is numerically equal to the sound pressure level of a continuous sound (for example, a sine wave) whose RMS pressure is

$$p_{\text{RMS2}} = p_{\text{p-p}} . \qquad (28)$$

Table 5 Peak pressure levels.

term	suggested symbol	definition	reference quantity (10lg*P*)	reference quantity (20lg*F*)
peak to peak sound pressure level for a transient signal	$L_{\text{p-p}}$	for a **transient signal** with **peak to peak sound pressure** equal to $p_{\text{p-p}}$, the quantity $10\log_{10}\frac{p_{\text{p-p}}^2}{p_{\text{ref}}^2}$ see (27) compare **zero to peak sound pressure level**	μPa²	μPa
zero to peak sound pressure level for a transient signal	$L_{\text{z-p}}$	for a **transient signal** with **peak sound pressure** equal to $p_{\text{z-p}}$, the quantity $10\log_{10}\frac{p_{\text{z-p}}^2}{p_{\text{ref}}^2}$ see (25) compare **peak to peak sound pressure level** NOTE: Peak sound pressure level is a widely used abbreviation of this term. This abbreviation is discouraged to avoid confusion with the standard definition of sound pressure level (SPL) as the RMS sound pressure, expressed as a level in decibels	μPa²	μPa

3.4 Other levels for which a definition might be needed

Further levels for which a definition might be needed, but is not included in any of Table 3, Table 4 or Table 5, are listed in Table 6.

Table 6 Other levels for which a definition might be needed.

term	symbol	definition	ref. quantity (10lg*P*)	ref. quantity (20lg*F*)
dipole source level			μPa² m²	μPa m
energy baffled source level			μPa² m² s	μPa m $s^{1/2}$
peak compressional sound pressure level			μPa²	μPa
peak rarefactional sound pressure level			μPa²	μPa
peak to peak pressure dipole source level			μPa² m²	μPa m
peak to peak pressure source level			μPa² m²	μPa m
sound exposure spectral density level			μPa² s Hz^{-1}	μPa $s^{1/2}$ $Hz^{-1/2}$
sound particle acceleration exposure level			μm² s^{-4} s	μm s^{-2} s
sound particle displacement exposure level			pm² s	pm $s^{1/2}$
sound particle velocity exposure level			nm² s^{-2} s	nm s^{-1} $s^{1/2}$
sound pressure exposure level			μPa² s	μPa $s^{1/2}$
zero to peak pressure dipole source level			μPa² m²	μPa m
zero to peak pressure source level			μPa² m²	μPa m

4 Use of the decibel alongside SI units

International standards for measuring and reporting underwater sound require a shared understanding of acoustical terminology, which in turn requires unambiguous definitions of the physical parameters to be reported and their units.

To supplement the terminology defined in Chapters 2 and 3, the need for unambiguous units is largely met by use of the SI, as SI units are well defined and widely recognised. While the decibel itself is not an SI unit, its use is so deeply entrenched in underwater acoustics that it would be unhelpful (and counterproductive) to develop a standard without clear practical advice on how to use the decibel in such a way that is compatible with the SI. The advice presented here is partly based on guidelines adopted by the US National Institute of Standards and Technology (NIST) for the use of the decibel alongside the SI [Taylor 1995, Taylor & Thompson 2008].

4.1 Standard reference values

Absolute quantities may be expressed in decibels by expressing them as ratios relative to standard reference values, which are listed in Table 7 in alphabetical order. These reference values are all SI units or standard sub-multiples of SI units.

Table 7 Reference values for use with the decibel.

term	**suggested symbol**	**definition**	**notes**
reference bandwidth		see **reference frequency**	
reference distance	r_{ref}	1 m	implied by national standard [ANSI 1989]
reference energy density	w_{ref}	1 pJ/m³	[Morfey 2001]
reference frequency	f_{ref}	1 Hz	National standard: [ANSI 1989]; more often used for bandwidth than for frequency
reference integration time	t_{ref}	1 s	no acoustical standard is known to the authors; use of t_{ref} = 1 s reflects usual practice in water
reference intensity	I_{ref}	1 pW/m²	National standard: [ANSI 1989]
reference particle acceleration	a_{ref}	1 μm/s²	[ISO 1683]
reference particle displacement	d_{ref}	1 pm	[ISO 1683]
reference particle velocity	u_{ref}	1 nm/s	[ISO 1683]
reference power	W_{ref}	1 pW	National standard: [ANSI 1989]
reference pressure for a sound in water	p_{ref}	1 μPa	International standard

4.2 Syntax for expressing levels relative to a specified reference value

4.2.1 *Guidelines*

The decibel (symbol dB) is a logarithmic unit of ratio. A change in noise spectral density level of 1 dB means that the noise spectral density has changed by a factor $10^{0.1} \approx 1.2589$, corresponding to either a 26 % increase or a 21 % decrease. Similar, a change in noise spectral density level of 10 dB means that the noise spectral density has changed by a factor 10, corresponding to either a 900 % increase or a 90 % decrease. Many acoustic parameters such as exposure E and RMS pressure p_{RMS} are routinely reported in logarithmic units as levels, becoming respectively sound exposure level (abbreviated SEL) and sound pressure level (abbreviated SPL). The precise relationships are [Morfey 2001]

$$\mathrm{SEL} = 10\log_{10}\frac{E}{{p_{\mathrm{ref}}}^2 t_{\mathrm{ref}}} \quad , \tag{29}$$

and

$$\mathrm{SPL} = 10\log_{10}\frac{{p_{\mathrm{RMS}}}^2}{{p_{\mathrm{ref}}}^2} . \tag{30}$$

These are special cases of the more general rule

$$L_x = 10\log_{10}\frac{x}{x_{\mathrm{ref}}} , \tag{31}$$

In each case, the units are decibels relative to the reference value or combination of reference values in the denominator. For sound in water, international standard values of p_{ref} and r_{ref} are one micropascal (1 μPa) and one metre (1 m). With this convention, the symbol for SEL would be L_E. Thus, an exposure of 1000 Pa^2 s, i.e.,

$$E = 10^{15}\ \mu\mathrm{Pa}^2\ \mathrm{s} \tag{32}$$

may be expressed in decibels in the form

$$L_E \equiv 10\log_{10}\frac{E}{1\,\mu\mathrm{Pa}^2\ \mathrm{s}} = 150\,\mathrm{dB} . \tag{33}$$

There are three pieces of information in (32): the symbol E, representing acoustic exposure; the unit $\mu\mathrm{Pa}^2$ s; and the value 10^{15}, a dimensionless number equal to the ratio of E to 1 $\mu\mathrm{Pa}^2$ s. To make the same statement in decibels, the same three pieces of information are needed, as illustrated by (33). Ambiguity is created if one or more are omitted.

Alternative versions of the same equation, compliant with national [AS 1991, p11; Thompson & Taylor 2008, p29] and international [IEC 1989, p11; IEEE 2004, p22] standards, are

$$L_E\left(\mathrm{re}\,1\,\mu\mathrm{Pa}^2\mathrm{s}\right) = 150\ \mathrm{dB} \tag{34}$$

and

$$L_{E/\left(1\,\mu\mathrm{Pa}^2\mathrm{s}\right)} = 150\ \mathrm{dB} . \tag{35}$$

A more common form that retains the same information, though not strictly compliant with these standards, is

$$L_E = 150\ \mathrm{dB}\ \mathrm{re}\,1\,\mu\mathrm{Pa}^2\ \mathrm{s} . \tag{36}$$

Much of the complication of Sec. 3.3 (Levels derived from peak sound pressure) is caused by the need to convert between a linear quantity (in this case pressure) and a logarithmic one (a "level") expressed in decibels, a self-inflicted burden that would be unnecessary if acoustic pressure were routinely reported in linear units.

To paraphrase Richard Feynman:

*[acousticians] have unfortunately chosen, arbitrarily, a funny unit called a decibel (*dB*), which is the unit transmission loss for which the ratio of the reduced rate of energy flow to the unreduced rate of energy flow is* $10^{-0.1}$*, which means that when*

the level of some physical parameter X, L_X, is equal to 1 dB*, the value of that physical parameter relative to the reference value X_0 is $X/X_0 = 10^{0.1}$. I am sorry that we do that, but that's the way it is for the acousticians.*

Feynman's criticism was addressed not at the decibel but at the electronvolt.[4] His implied question was whether the benefit of convenience to particle physicists when comparing the energy of elementary particles was worth the price paid in the form of a barrier to comprehension to outsiders (scientists and non-scientists alike) not familiar with this particular convention. The purpose of borrowing his words is to make the point that the same question can be asked of the decibel, and to encourage authors to be very clear about the physical quantity and the reference value when reporting acoustical information in decibels.

It is common practice in underwater acoustics to attach subscripts and other qualifiers to the dB symbol (e.g., $\mathrm{dB_{peak}}$, $\mathrm{dB_{RMS}}$, dBSPL). These qualifiers are avoided, as they convey no additional information if the principles of Section 4.3 are followed, can introduce ambiguity if the meaning of the qualifier is not explained, and their use is deprecated by international standards organisations [IEC, ISO].

4.2.2 *Rules for the selection of reference value*

The purpose of this section is to provide guidance for the choice of reference value. The IEC standard [IEC 2002] defines field quantities and power quantities and specifies reference values for these. Specifically, "a quantity the square of which is proportional to power when it acts on a linear system is here called a *field quantity*, general symbol *F*", while "a quantity that is proportional to power is called a *power quantity*, general symbol *P*. In many cases also energy-related quantities are labelled as power quantities in this context". Examples of field quantities are voltage, sound pressure, particle speed and force. Examples of power quantities are active power, reactive power and acoustic power. Also mentioned are "corresponding power densities", which might be interpreted as acoustic intensity (in watts per square metre) or power spectral density (in watts per hertz). The decibel is widely used to express levels of acoustical quantities that are not mentioned explicitly by the IEC standard, so the question arises what the appropriate reference value is for such quantities. A discussion of possible interpretations is provided below, followed by a description of three (alternative) specific options. The choice between these three options is left to the user of this standard.

4.2.2.1 *Possible interpretations of the IEC standards*

Consider first the definition of sound pressure level as ten times the logarithm of the mean square pressure. The mean square pressure is proportional to power and is therefore a power quantity. The reference value inferred from this reasoning is 1 $\mu\mathrm{Pa}^2$. On the other hand, sound pressure level can be defined just as well as twenty times the logarithm of the RMS pressure. The RMS pressure is a field quantity because its square is proportional to power. The reference value inferred

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[4] Feynman's own words [http://www.numericana.com/answer/feynman.htm] are "[physicists] have unfortunately chosen, arbitrarily, a funny unit called an electronvolt (eV), which is the energy needed to move an electron through a potential difference of one volt, and that turns out to be about 1.6×10^{-19} J . I am sorry that we do that, but that's the way it is for the physicists."

The definition of "decibel" is quoted from [Horton 1959, p44]. The explanation "when L_X = 1 dB, $X/X_0 = 10^{0.1}$." is (paraphrased) from [Taylor & Thompson 2008]

from this reasoning is 1 μPa. The two definitions are mathematically identical, yet they result in different reference values.
Consider also the quantity peak sound pressure (in any one of its forms).
The square of this quantity is not proportional to power and the IEC standard provides no guidance in choosing a suitable reference value for it.

A third case is the source level, which is defined in Table 4 in two different ways, the first in terms of the sound pressure level referred to a standard reference distance, and the second in terms of the source factor. Starting with the first definition, the reference value for source level is the same as that for sound pressure level, which we have established is either 1 μPa or 1 μPa². Alternatively, for the second definition, defined as ten times the logarithm of the source factor. The source factor is proportional to power, so its reference value would be 1 μPa² m². On the other hand, a mathematically identical definition can be made as twenty times the logarithm of the square root of the source factor, the reference value for which is 1 μPa m.

For the spectral density of the mean square pressure, a similar argument can be made, resulting in a choice for the reference value between 1 μPa²/Hz and 1 μPa/Hz$^{1/2}$.

One possible criterion for choosing between the above reference values is to follow established convention. In other words, if there is a long tradition for the use of a particular reference value, and no good reason for changing this value, then this value would make a sensible choice (this is listed as Option 1). This route helps in cases for which an established convention exists, but not otherwise. Two further options (Options 2 and 3) are provided, intended to cope with situations for which no well established convention exists. The consistent use of either one makes explicit the dimensions (and implied units) of the physical parameters represented by the decibel levels.

In any single document, a choice is made between these options. Once this choice is made in that document, it is used consistently throughout. Thus, while options 2 and 3 are completely equivalent, they are not interchangeable.

4.2.2.2 *Option 1: follow established convention*

Where a widespread convention exists for the use of a particular reference value, and this use is supported by a pertinent international standard, that reference value is used, and the chosen standard is cited. An example is the ubiquitous use of 1 μPa (and not 1 μPa²) as a reference value of sound pressure level.

4.2.2.3 *Option 2: 10lgP rule*

Levels in decibels are considered to be logarithmic measures of ratios of power (represented by the symbol *P*). Thus, the level represents a power ratio of the form

$$L_P \equiv 10\log_{10}\frac{P}{P_{\mathrm{ref}}}, \qquad (37)$$

and the reference quantity P_{ref} is proportional to power, such as μPa² if *P* is the mean square pressure, μPa² m² if *P* is the source factor, or μPa²/Hz if *P* is the spectral density.

Here and throughout, application of (37) is referred to as use of the “10lg*P* rule”.

4.2.2.4 *Option 3: 20lgF*

Levels in decibels are considered to be logarithmic measures of ratios of field quantities (represented by the symbol *F*). Thus, the level represents a field quantity ratio of the form

$$L_F \equiv 20\log_{10}\frac{F}{F_{\mathrm{ref}}}, \tag{38}$$

and the reference quantity F_{ref} is proportional to the square root of power, such as µPa if *F* is RMS pressure, µPa m if *F* is the square root of the source factor, or µPa/Hz$^{1/2}$ if *F* is the square root of the spectral density.

Here and throughout, application of (38) is referred to as use of the 20lg*F* rule.

4.3 Principles and specific examples

The symbol for the decibel is dB. While the decibel is not recognized as an SI unit, its use alongside SI units is accepted by the International Committee for Weights and Measures (CIPM) and at least one national standards body [Taylor 1995, B. N. Taylor, Guide for the Use of the International System of Units (SI), NIST Special Publication 811, 1995 Edition, United States Department of Commerce, National Institute of Standards and Technology (1995).]. The following three principles, described in more detail below, are followed when expressing the value of a level in decibels:

- state the physical parameter represented by the level;
- state the reference value of that physical parameter;
- the reference value is always an SI unit.

4.3.1 *State the physical parameter clearly*

The general rule is stated first, followed by three specific cases.

4.3.1.1 *General rule*

The physical quantity to be represented by a level is stated either explicitly by means of a definition or implicitly by using a standard term such as **sound pressure level** or **sound exposure level**:

The received unweighted sound exposure level is 80 dB re 1 µPa^2 s
The received unweighted sound exposure level is 80 dB re 1 µPa s$^{1/2}$

not

The received level is 80 dB re 1 µPa^2 s
The received level is 80 dB re 1 µPa s$^{1/2}$

4.3.1.2 *State the bandwidth clearly*

The frequency band of any processing, including time domain or frequency domain filters, averaging bandwidth, or integration bandwidth is stated explicitly. This need not be on every occurrence. If the same frequency band is used throughout it is sufficient to say so once at the beginning. Knowledge of the bandwidth in which a level is measured and reported is especially important for broadband signals.

4.3.1.3 *State the averaging time clearly*

The averaging time for measured RMS values is stated explicitly.[5] This need not be on every occurrence. If the same averaging time is used throughout it is sufficient to say so once at the beginning. Knowledge of the averaging time in which a level is measured is especially important for transient signals.

4.3.1.4 *State the weighting clearly*

Any weighting used is specified, either implicitly by use of standard terminology (and citing the standard in which an explicit statement of the weighting can be found), or by stating the weighting function explicitly. Correct examples include:

The M-weighted sound exposure level for low frequency cetaceans is 80 dB re 1 µPa^2 s.

The sound level, weighted using the filter specified in Table X, is 100 dB re 1 µPa^2 (where Table X specifies the weighting applied in decibels over the applicable frequency range).

Incorrect examples include:

The sound exposure level is 80 dB re 1 µPa^2 s.
The weighted sound level is 100 dB re 1 µPa^2.

4.3.1.5 *Report physical parameters in SI units where needed*

In some situations, levels reported in decibels might be ambiguous, either because a definition for the corresponding level is not available or because there exist more than one conflicting definitions. In situations where ambiguity might otherwise arise, physical parameters are reported in SI units whether or not they are also reported in decibels. For example, the authors of a document reporting peak pressure as a level might choose to report the value of peak pressure in pascals if they consider that the level in decibels could be misinterpreted.

4.3.2 *State the reference value clearly*

The reference value is always stated explicitly, even when a standard value is used. The reference value need not be stated in every occurrence, provided that explicit mention is made of the intention not to do so, and that the chosen reference value is stated on first use. The reference value is always a product of reference values (or their reciprocals) from Table 7. Consistent use is made either of 10lgP rule (option 1), 20lgA rule (option 2) or reference values from a stated international standard (option 3). Correct examples include

The sound pressure level is 80 dB re 1 µPa

The sound pressure level is 80 dB re 1 µPa^2; the MSP spectral density level is 50 dB re 1 µPa^2/Hz.

The sound pressure level is 80 dB re 1 µPa; the MSP spectral density level is 50 dB re 1 µPa/Hz$^{1/2}$.

The source level is 180 dB re 1 µPa^2 m^2; the sound exposure level is 170 dB re 1 µPa^2 s.

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[5] This requirement holds also for simulated RMS values, except for situations involving a statistically stationary sound

Incorrect examples include

The sound pressure level is 80 dB.
The source level is 180 dB re 1 µPa m; the sound exposure level is 170 dB re 1 µPa² s.

The numerical value in the reference value may be omitted if equal to 1: “The sound pressure level is 80 dB re µPa”.

4.3.3 *The reference value is always an SI unit*

The reference value is always an SI unit or a standard sub-multiple of an SI unit. Subscripts and other qualifiers appended to SI units are avoided[6]. [IEC 2002, ISO 2007]. (Instead, such qualifiers are replaced by an explicit statement of the physical quantity intended.) This precludes shorthand notation such as “1 µPa @ 1 m” to indicate a reference distance of 1 m.

Table 8 Avoid subscripts and qualifiers to SI unit symbols.

correct examples	**incorrect examples**
The source level is 180 dB re 1 µPa m **The source level is 180 dB re 1 µPa² m²** **The source level referred to a distance of 1 m is 180 dB re 1 µPa**	**The source level is 180 dB re 1 µPa @ 1 m**
The zero to peak sound pressure level is 80 dB re 1 µPa	**The sound pressure level is 80 dB re 1 µPapeak**
The sound pressure level is 80 dB re 1 µPa	**The sound pressure level is 80 dB re 1 µPa$_{\text{rms}}$**

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[6] see http://physics.nist.gov/Pubs/SP811/sec07.html#7.4

7.4 Unacceptability of attaching information to units

“When one gives the value of a quantity, it is incorrect to attach letters or other symbols to the unit in order to provide information about the quantity or its conditions of measurement. Instead, the letters or other symbols should be attached to the quantity.

Example: Vmax = 1000 V but not: V = 1000 Vmax

Note: V is a quantity symbol for potential difference”

5 Definitions of non-SI units and measurement scales

Thanks to the widespread international acceptance of the SI [BIPM www], only units falling outside this system need to be defined. Symbols for non-SI units are always defined on first use, including a conversion to its SI equivalent where possible to do so.

The definitions in this section are grouped into four categories:

- non-SI units of time, distance, speed and angle (Table 9)
- logarithmic units (Table 10)
- units of information (Table 11)
- measurement scales (Table 12)

Within each category, the definitions are provided in alphabetical order.

5.1 Non-SI units of time, distance, speed and angle

In the context of acoustical measurements at sea it might sometimes be appropriate to use non-SI units, especially for specifying times of day or geographical co-ordinates. Some examples are given in Table 9.

Table 9 Units of time, distance, speed and angle.

term	symbol	definition	notes
day	d	unit of time equal to 24 **hours**; 1 d = 24 h	see [IEEE 2004]
degree	º	unit of angle equal to π/180 radians, i.e., 1/360th of a full circle	see [IEEE 2004]
hour	h	unit of time equal to 60 **minutes**; 1 h = 60 min	see [IEEE 2004]
knot	kn	unit of speed equal to one **nautical mile** per **hour**; 1 kn = (1852/3600) m/s ≈ 0.5144 m/s; 9 kn = 4.63 m/s, exactly	see [IEEE 2004]
minute	min	unit of time equal to 60 seconds; 1 min = 60 s	see [IEEE 2004]
minute (of arc)	‘	unit of angle equal to 1/60th of a **degree**	see [IEEE 2004]
nautical mile	nmi	unit of distance equal to 1852 m; 1 nmi = 1.852 km	see [IEEE 2004]
second (of arc)	“	unit of angle equal to 1/60th of a **minute**	see [IEEE 2004]

5.2 Logarithmic units

Commonly used logarithmic units, including the bel and decibel, are defined in Table 10.

Table 10 Logarithmic units.

term	symbol	definition	notes
bel		logarithmic unit of power ratio defined such that a factor 10 change in power corresponds to a change in power level of one bel. See [ISO 2007] 8-22.a to 8-24.a	1 bel = 10 dB in order to avoid risk of confusion with the **byte**, the symbol B is not used to mean bel except as part of the symbol for the **decibel** (dB)
decade	dec	logarithmic unit of frequency ratio defined such that a factor 10 change in frequency corresponds to one decade. See [ISO 2007] 8-3b	
decibel	dB	logarithmic unit of power ratio defined as one tenth of a **bel**	1 bel = 10 dB
neper	Np	logarithmic unit of amplitude ratio defined such that a factor e (approximately 2.7183) change in amplitude corresponds to a change in amplitude level of one neper	a change in amplitude level of one neper corresponds to a change in power level of $10\log_{10}(e^2)$ dB ≈ 8.686 dB
octave	oct	logarithmic unit of frequency ratio defined such that a factor 2 change in frequency corresponds to one octave. See [ISO 2007] 8-3a	
phi unit	ϕ	logarithmic unit of reciprocal sediment grain diameter, defined such that a factor 2 change in grain diameter corresponds to a change in grain size of one phi unit	see **Udden-Wentworth scale**
third octave (1)		logarithmic unit of frequency ratio defined as one third of an **octave;** this frequency ratio is $2^{1/3} \approx 1.2599$	
third octave (2)	ddec	logarithmic unit of frequency ratio defined as one tenth of a **decade** (a decidecade): this frequency ratio is $10^{0.1} \approx 1.2589$	[ANSI S1.6 1984]; one **third octave (2)** is smaller than one **third octave (1)** by 0.08%

5.3 Units of information

Units of information storage and data communication are relevant because acoustical measurements are usually stored in digital form, and because measured data might be transferred across an acoustical communications network.
The term “megabyte” is used by some to mean 1024^2 bytes, while others reserve this term for the quantity 1000^2 bytes. Still others use it to mean 1024000 bytes. This ambiguity was identified and resolved in 1998 by the International Electrotechnical Commission (IEC) [iec 1998]. The IEC standard is also used by the IEEE [ref]. The iec definitions are included in Table 11, with some additions pertinent to underwater acoustic communications.

Table 11 Units of information.

term	symbol	definition	notes
bit	bit	binary unit of information storage	see [IEC 2005]
byte	B	unit of information storage, equal to eight **bits** unless otherwise specified	see [IEC 2005]
kibibit, mebibit, gibibit … yobibit	Kibit, Mibit, Gibit … Yibit	units of information storage equal to 1024 1024^2, 1024^3 … 1024^8 **bits**	see [IEC 2005]
kibibyte, mebibyte, gibibyte … yobibyte	KiB, MiB, GiB … YiB	units of information storage equal to 1024 1024^2, 1024^3 … 1024^8 **bytes**	see [IEC 2005]
kilobit, megabit, gigabit … yottabit	kbit, Mbit, Gbit … Ybit	units of information storage obtained by combining the bit with SI prefixes kilo-, mega-, giga- … yotta-, equal to 1000 1000^2, 1000^3 … 1000^8 **bits**	see [IEC 2005]; see also **millibit …**
kilobyte, megabyte, gigabyte … yottabyte	kB, MB, GB … YB	units of information storage obtained by combining the byte with SI prefixes kilo-, mega-, giga- … yotta-, equal to 1000 1000^2, 1000^3 … 1000^8 **bytes**	see [IEC 2005]; fractions of a byte such as millibyte (and decibyte in particular) are avoided, but see **millibit …**
millibit, microbit, nanobit … yoctobit	mbit, μbit, nbit … ybit	units of information obtained by combining the bit with SI prefixes milli-, micro-, nano- … yocto-, equal to 1000^{-1} 1000^{-2}, 1000^{-3} … 1000^{-8} **bits**	not defined explicitly in the IEC standard; used for expressing low data rates, as in “a communication rate of 30 mbit/s (30 millibits per second, meaning that 30 bits are transferred every 1000 seconds)”; see also **kilobit …**

5.4 Measurement scales

The correct interpretation of acoustical measurements at sea requires an understanding of the conditions prevailing during the measurements. In order to provide unambiguous information about these conditions, a standard vocabulary is needed to describe, for example, the sea surface and the seabed. Some relevant measurement scales are described in Table 12.

Table 12 Definitions of measurement scales relevant to underwater sound.

term	definition	notes
Beaufort force	see **Beaufort scale**	
Beaufort scale	qualitative scale relating conditions at sea to a number between 0 and 12 known as **Beaufort force** [WMO 1970]	The **Beaufort force** is sometimes related to wind speed at a specified measurement height, for example using WMO Code 1100 [NOAA http]. The use of Code 1100 is known to produce a bias in wind speed of order 1 m/s. More accurate scales have been developed [Kent & Taylor 1997] but are not widely used. See [Ainslie 2010, pp 159-165].
pH scale	logarithmic scale of hydrogen ion concentration in water defined such that a factor 10 change in concentration corresponds to a change in pH of one pH unit [Millero 2006]	Two different pH scales in widespread use for seawater are the NBS[7] scale (predominant in acoustics literature) and SWS (seawater scale, recommended by a UNESCO report [Dickson & Millero 1987]). These two scales differ by 0.15 pH units [Brewer et al 1995, Ainslie 2010, p138, p664].
sea state	quantitative scale relating ranges of significant wave height to a number between 0 and 9 known as 'sea state'	A widely used sea state scale is described by WMO code 3700 [NODC www]. See also [Ainslie 2010, p166].
Udden-Wentworth scale	scale of marine sediments in terms of grain diameter introduced by [Udden 1914] and refined by [Wentworth 1922]	see [Krumbein & Sloss 1963] and [Ainslie 2010, p174]; see also **phi unit**
Wentworth scale	see **Udden-Wentworth scale**	

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[7] US National Bureau of Standards, now the National Institute of Standards and Technology (NIST)

6 Way ahead

Future objectives concerning the development and acceptance of acoustical terminology related to underwater sound include:

- the promotion and use of this standard at national and international levels (consolidate use in Netherlands; seek international acceptance in Europe; seek collaboration with organisations like the Acoustical Society of America (ASA) and the International Organization for Standardization (ISO) for obtaining an international consensus beyond Europe);
- a broad consensus for the definitions of source level proposed in Appendix B applicable to air-guns and explosives;
- a practical definition of source level for an impact pile driver or a suitable alternative.

In order to meet these objectives, possible courses of action include:

- propose the use of this document as a basis for a new ISO standard on acoustical terminology for underwater sound;
- draw attention to the existence of this document at international conferences and workshops;
- compose a non-technical article about the need for standardisation and the existence of this document for publication in specialist non-peer reviewed journal such as Acoustics Today or Acoustics Bulletin;
- compose a technical article about the definition of source level in a peer reviewed journal such as Applied Acoustics;
- create a web page dedicated to definitions of units and standard terminology, including explanations of these in a language accessible all stakeholders such as regulators, industry, NGOs and students.

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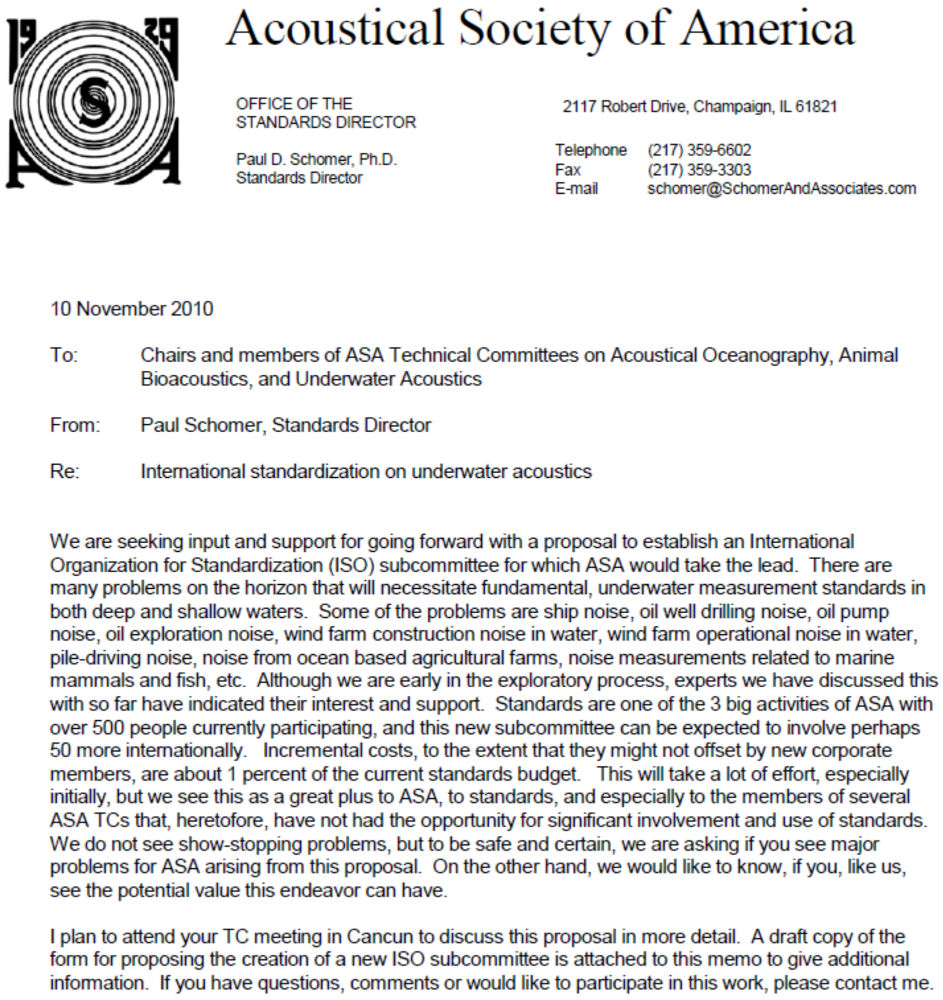
9 Signature

The Hague, September 2011 TNO

P. Hendriksen
Head of department

M.A.Ainslie
Editor

A Letter from ASA Standards Director



Acoustical Society of America

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10 November 2010

To: Chairs and members of ASA Technical Committees on Acoustical Oceanography, Animal Bioacoustics, and Underwater Acoustics

From: Paul Schomer, Standards Director

Re: International standardization on underwater acoustics

We are seeking input and support for going forward with a proposal to establish an International Organization for Standardization (ISO) subcommittee for which ASA would take the lead. There are many problems on the horizon that will necessitate fundamental, underwater measurement standards in both deep and shallow waters. Some of the problems are ship noise, oil well drilling noise, oil pump noise, oil exploration noise, wind farm construction noise in water, wind farm operational noise in water, pile-driving noise, noise from ocean based agricultural farms, noise measurements related to marine mammals and fish, etc. Although we are early in the exploratory process, experts we have discussed this with so far have indicated their interest and support. Standards are one of the 3 big activities of ASA with over 500 people currently participating, and this new subcommittee can be expected to involve perhaps 50 more internationally. Incremental costs, to the extent that they might not offset by new corporate members, are about 1 percent of the current standards budget. This will take a lot of effort, especially initially, but we see this as a great plus to ASA, to standards, and especially to the members of several ASA TCs that, heretofore, have not had the opportunity for significant involvement and use of standards. We do not see show-stopping problems, but to be safe and certain, we are asking if you see major problems for ASA arising from this proposal. On the other hand, we would like to know, if you, like us, see the potential value this endeavor can have.

I plan to attend your TC meeting in Cancun to discuss this proposal in more detail. A draft copy of the form for proposing the creation of a new ISO subcommittee is attached to this memo to give additional information. If you have questions, comments or would like to participate in this work, please contact me.

B Towards an Internationally Accepted Definition of "Source Level"

version: 1.0
authors: M. A. Ainslie (TNO), S. P. Robinson (NPL), V. Humphrey (ISVR),
C. A. F. de Jong (TNO), P. R. White (ISVR)

B.1 Introduction

The purpose of this note is to seek an international consensus for a definition of "source level" in the context of underwater sound. [Urick 1983] defines this quantity (implicitly) as the far-field sound pressure level, scaled back to a standard reference distance by correcting for propagation loss from a point source. The ANSI [ANSI 1994] and IEC [IEC www] definitions that exist are applicable only to very simple situations such as a point source in free space. Urick's definition is valid for real (finite) sources and real world conditions, and different ways of making this definition explicit are explored. The purpose is to compose definitions that could be accepted as part of an international (e.g., IEC) standard.

The reason for providing a definition for "source level" is to enable unambiguous use of this term, by ourselves and others. The term is used and will continue to be used for many different purposes, whether or not we supply definitions.
For example, EU plans to achieve "Good Environmental Status" include the monitoring of underwater sound. One of the metrics that have been proposed [EC 2010] for doing so involves counting the number of times a source exceeding a particular source level threshold is used[8].

A definition is needed (in order of increasing difficulty) at least for sonar, air guns, explosives and impact pile driving. It is expected that more than one definition will be necessary to cover all of these. From a Dutch (TNO) perspective, the most important is the pile driver, because TNO has been asked to specify measurement standards for the next round of wind farm construction in the Netherlands in 2012. Unfortunately, the pile driver is also the most difficult case. (It is not obvious that it even makes sense to talk of the source level of an object that is both firmly attached to the seabed and partly sticking out in air, but we can try).

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[8] The precise wording of the TG11 report [Tasker et al 2010] included the term "source level" in draft versions, but this term was dropped in the final wording. The present authors understand that no change in meaning was intended in doing so.

B.2 Standard definitions adopted from other sources

The suggested definitions make use of the terms “sound pressure level” (abbreviated SPL) and “source factor” (symbol *S*). These are defined as follows.

SPL is defined as the mean square pressure converted to decibels: [IEC www, Morfey 2001]

$$\mathrm{SPL} \equiv 10\log_{10}\frac{p_{\mathrm{RMS}}{}^2}{p_{\mathrm{ref}}{}^2}$$

where
p_{RMS} = RMS acoustic pressure
p_{ref} = reference pressure (usually 1 μPa in water)

The definitions also make use of a reference distance, denoted r_{ref}, usually equal to 1 m.

The “source factor” *S* is defined as [Ainslie 2010c]

$$S \equiv p_{\mathrm{FF}}{}^2(r)r^2$$

where
$p_{\mathrm{FF}}(r)$ = far-field (and free-field) RMS acoustic pressure at distance r

B.3 Monopole definition

B.3.1 *Continuous source: “source level”*

Two definitions of source level are proposed in Table 13 for a finite directional continuous[9] source (e.g., sonar transducer) in a real[10] medium (locally uniform, of density ρ_0 and sound speed c_0 at the source position). Of these, definition 1 is closest to the conventional Urick definition, and expressed in terms of a sound pressure level at 1 m distance from an equivalent monopole. Definition 2 makes use of the concept of source factor.

Definition 2 is related to radiant intensity as follows. First write

$$S = p_{\mathrm{FF}}{}^2 r^2 .$$

Then express the mean square pressure in terms of free-field and far-field intensity *I*

$$p_{\mathrm{FF}}{}^2 = \rho_0 c_0 I$$

and the distance *r* as area per unit solid angle

---

[9] by “continuous source” is meant one whose duration is long enough to justify thinking in terms of a constant RMS pressure at the receiver

[10] by “real medium” is meant a non-uniform, absorbing medium

$$r^2 = \frac{\delta A}{\delta \Omega}.$$

It then follows that the source factor is related to radiant intensity (power per unit solid angle, denoted $\delta W / \delta \Omega$):

$$S = \rho_0 c_0 \frac{\delta W}{\delta \Omega},$$

where

$$\delta W = I \delta A.$$

Table 13 Definition of "source level" for a continuous source.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of sound pressure level (SPL) referred to standard reference distance r_{ref}**	**DEFINITION 2 equivalent definition cast in terms of source factor (*S*)**
finite directional source (e.g., sonar transducer) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	SPL at a standard reference distance r_{ref} from a point monopole, placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, that produces the same far-field radiant intensity in a specified direction from the actual source if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium.	The value of $10\log_{10}\frac{S}{{p_{\mathrm{ref}}}^2{r_{\mathrm{ref}}}^2}$ that would exist on the transducer axis if the same directional source were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.
proposed symbol or abbreviation	$\mathrm{SL}_{r_{\mathrm{ref}}}$	SL
unit	dB	dB
reference value	1 μPa²	1 μPa² m²
example of use[11]	The source level referred to a distance of 1 m is 210 dB relative to 1 μPa². In equation form $\mathrm{SL}_{1\mathrm{m}}$ = 210 dB re 1 μPa²	The source level is 210 dB relative to 1 μPa² m². In equation form SL = 210 dB re 1 μPa² m²

B.3.2 *Transient source: "energy source level"*

Unweighted SEL is defined as the time integrated acoustic pressure squared converted to decibels:

$$\mathrm{SEL} \equiv 10\log_{10}\frac{\int p(t)^2\,\mathrm{d}t}{{p_{\mathrm{ref}}}^2 t_{\mathrm{ref}}}$$

where

$p(t)$ = instantaneous acoustic pressure

---

[11] The alternative shorthand "SL = 210 dB re 1 μPa @ 1 m" is often encountered. The wording of Table 13 is preferred, to avoid mixing the definition of source level and its unit, and to avoid giving the incorrect impression that source level is the sound pressure level at 1 m distance from the source. The intended meaning is the same.

t_{ref} = reference time

Unlike for p_{ref} and r_{ref} there is no internationally recognised standard value for t_{ref} known to the authors. A value of t_{ref} = 1 s is proposed for sound in water.

We further define "instantaneous source factor" $S(t)$ as

$$S(t) \equiv p_{\mathrm{FF}}{}^2(r;t)r^2$$

where

$p_{\mathrm{FF}}(r;t)$ = far-field (and free-field) instantaneous acoustic pressure at distance r

Table 14 Definition of "energy source level" for a transient source.

scenario/ applicability	**DEFINITION 1** **conventional definition cast in terms of unweighted sound exposure level (SEL) referred to standard reference distance r_{ref}**	**DEFINITION 2** **equivalent definition cast in terms of time-integrated source factor**
finite directional transient source in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	SEL at a standard reference distance r_{ref} from a point monopole, placed in a lossless uniform medium (of density ρ_0 and sound speed c_0 and extending to infinity in all directions), that produces the same far-field radiant intensity in a specified direction from the actual source if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium.	The value of $10\log_{10}\frac{\int S(t)\mathrm{d}t}{p_{\mathrm{ref}}{}^2 r_{\mathrm{ref}}{}^2 t_{\mathrm{ref}}}$ that would exist on the transducer axis if the same directional source were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.
proposed symbol or abbreviation	$\mathrm{SL}_{\mathrm{E},r_{\mathrm{ref}}}$	$\mathrm{SL_E}$
unit	dB	dB
reference value	1 μPa² s	1 μPa² m² s
example of use	The energy source level referred to a distance of 1 m is 210 dB relative to 1 μPa² s. In equation form $\mathrm{SL}_{\mathrm{E,1m}}$ = 210 dB re 1 μPa² s	The energy source level is 210 dB relative to 1 μPa² m² s. In equation form $\mathrm{SL_E}$ = 210 dB re 1 μPa² m² s

B.4 Dipole definition (continuous source near sea surface)

B.4.1 *“dipole source level”*

It is common to parametrise near surface sources such as surface ships or air guns in terms of the strength of the dipole formed by the source and its surface image, rather than that of the original monopole. A suitable definition of “dipole source level” for such sources is explored next.

Table 15 Definition of “dipole source level” for a continuous source.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of sound pressure level (SPL) referred to standard reference distance r_ref**	**DEFINITION 2 equivalent definition cast in terms of source factor (*S*)**
finite directional source (e.g., sonar transducer) combined with its image in a perfectly reflecting surface (with π phase change) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	SPL at a standard reference distance r_ref from a point monopole, placed in a lossless uniform medium (of density ρ_0 and sound speed c_0 and extending to infinity in all directions), that produces the same far-field radiant intensity in a specified direction from the actual source+image if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium.	The value of $10\log_{10}\frac{S}{p_\mathrm{ref}^2 r_\mathrm{ref}^2}$ that would exist in a specified direction if the same directional source+image were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.
proposed symbol or abbreviation	$\mathrm{SL}_{\mathrm{dp},r_\mathrm{ref}}$	SL_dp
unit	dB	dB
reference value	1 μPa²	1 μPa² m²
example of use	The on-axis dipole source level referred to a distance of 1 m is 210 dB relative to 1 μPa². In equation form $\mathrm{SL}_\mathrm{dp,1m}$ = 210 dB re 1 μPa²	The on-axis dipole source level is 210 dB relative to 1 μPa² m². In equation form SL_dp = 210 dB re 1 μPa² m²

B.4.2 *“areic dipole source level”*

Some types of near surface sound source, such as wind or rain noise, are extended sources that can be idealised as an infinite sheet. The definitions presented here are for dipoles created by sheet of point monopoles. Generalisations to sources more complicated than point dipoles are possible, but not considered necessary for the present purpose.

Definition 2 uses the areic source factor S_A, defined for an incremental area δA (in a specified frequency band) as:

$$S_A = \frac{\delta S}{\delta A}\,.$$

Table 16 Definition of "areic dipole source level" for a continuous infinite sheet source.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of sound pressure level (SPL) referred to standard reference distance r_{ref}**	**DEFINITION 2 equivalent definition cast in terms of source factor**
sheet of dipoles created by a sheet of uncorrelated point monopoles combined with their surface images in a perfectly reflecting surface (with π phase change) (e.g., rain noise) and in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	Suggestions invited	the value of $10\log_{10}\frac{S_A}{p_{\mathrm{ref}}^2}$ due to the same sheet of dipoles if placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions
proposed symbol or abbreviation		SL_A
unit		dB
reference value		1 μPa²
example of use		The areic dipole source level in the frequency band from 10 Hz to 100 Hz is 45 dB relative to 1 μPa². In equation form SL_A = 65 dB re 1 μPa² or (equivalently) SL_A = 65 dB re 1 μPa² m² /m²

B.5 Definitions related to peak pressure, including "peak pressure level" and "peak pressure source level" (transient source)

B.5.1 "peak pressure", "peak pressure level" and related quantities

The following terminology is used:

Table 17 Definition of peak compressional and rarefactional pressures, peak acoustic pressure and static pressure

term	definition	notes
peak compressional acoustic pressure	$p_{\mathrm{peak,c}} := P_{\mathrm{max}} - P_0$	p_{max} is the maximum value of the instantaneous total pressure; p_0 is the static pressure
peak rarefactional acoustic pressure	$p_{\mathrm{peak,r}} := P_0 - P_{\mathrm{min}}$	p_{min} is the minimum value of the instantaneous total pressure [IEC 802]
static pressure	P_0	pressure that would exist in the absence of sound waves [ISO 2007]
peak acoustic pressure	$p_{\mathrm{peak}} := \max(p_{\mathrm{peak,c}}, p_{\mathrm{peak,r}})$	always positive

Table 18 Definition of levels related to peak acoustic pressure.

term	definition	notes
peak compressional pressure level	$L_{\mathrm{peak,c}} \equiv 10\log_{10}\dfrac{p_{\mathrm{peak,c}}^2}{p_{\mathrm{ref}}^2}$	peak compressional pressure expressed in decibels
peak rarefactional pressure level	$L_{\mathrm{peak,r}} \equiv 10\log_{10}\dfrac{p_{\mathrm{peak,r}}^2}{p_{\mathrm{ref}}^2}$	peak rarefactional pressure expressed in decibels
peak pressure level[12]	$L_{\mathrm{peak}} \equiv 10\log_{10}\dfrac{p_{\mathrm{peak}}^2}{p_{\mathrm{ref}}^2}$	peak acoustic pressure expressed in decibels

While some argue that the definition of the decibel as a (logarithmic) unit of power ratio does not permit its use as a unit of peak pressure in this way [Horton 1952, Horton 1954, Carey 2006], the use of "peak pressure level" in decibels, with the meaning given in Table 17 (and with the same value of p_{ref} as for SPL, i.e., 1 μPa), is widespread. By including it in the table, the authors intend not to condone this widespread use, but to acknowledge it and to offer a means of making it unambiguous. [13]

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[12] Also used (often synonymously with "peak pressure level") are the terms "peak sound pressure level", and even "peak SPL". The authors discourage this use to avoid confusion with the standard definition of sound pressure level (SPL) as the RMS sound pressure, expressed as a level in decibels.

[13] With these definitions, the numerical value of the peak pressure level of a sine wave is 10lg2 ≈ 3.01 dB higher than the numerical value of its sound pressure level.

B.5.2 *“peak pressure source level”*

Definition 2 uses the peak source factor S_peak defined as the product of the far-field and free-field peak acoustic pressure squared and distance squared, in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions.

Table 19 Definition of “peak pressure source level” for a transient source.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of peak pressure level referred to standard reference distance r_ref**	**DEFINITION 2 equivalent definition cast in terms of peak source factor**
finite directional source in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	peak pressure level at a standard reference distance r_ref from a point monopole, placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, that produces the same value of S_peak as would exist on the transducer axis of the actual source if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium.	The value of $10\log_{10}\frac{S_\text{peak}}{p_\text{ref}^2 r_\text{ref}^2}$ that would exist on the transducer axis if the same directional source were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.
proposed symbol or abbreviation	$\mathrm{SL}_{\text{peak},r_\text{ref}}$	SL_peak
unit	dB	dB
reference value	1 μPa²	1 μPa² m²
example of use	The peak pressure source level referred to a distance of 1 m is 210 dB relative to 1 μPa². In equation form $\mathrm{SL}_\text{peak,1m}$ = 210 dB re 1 μPa²	The peak pressure source level is 210 dB relative to 1 μPa² m². In equation form SL_peak = 210 dB re 1 μPa² m²

B.5.3 *“peak pressure dipole source level”*

Table 20 Definition of “peak pressure dipole source level” for a transient source.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of peak pressure level referred to standard reference distance r_{ref}**	**DEFINITION 2 equivalent definition cast in terms of peak source factor**
finite directional source combined with its image in a perfectly reflecting surface (with π phase change) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	peak pressure level at a standard reference distance r_{ref} from a point monopole, placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, that produces the same value of S_{peak} as would exist in the far field and in a specified direction from the actual source+image if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium	The value of $10\log_{10}\frac{S_{\mathrm{peak}}}{{p_{\mathrm{ref}}}^2{r_{\mathrm{ref}}}^2}$ that would exist in a specified direction if the same directional source+image were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.

B.5.4 *“energy baffled source level”*

Here the definition of “energy source level” is generalised first to the case of a source close to the sea surface (definition A), then to the source attached to a partially reflecting boundary representing the seabed (definitions B and C).
In the latter case the actual source and boundary are considered as a single compound source; to keep things tractable the source + boundary are considered first in an infinite uniform medium (definition B), before considering the complications of a real medium (definition C).

Table 21 Definition of “energy baffled source level” for a transient source close to or in contact with a reflecting boundary.

scenario/ applicability	**DEFINITION 1 conventional definition cast in terms of unweighted sound exposure level (SEL) referred to standard reference distance r_ref**	**DEFINITION 2 equivalent definition cast in terms of time-integrated source factor**
A) finite directional transient source (e.g., sonar transducer) combined with its image in a perfectly reflecting surface (with π phase change) in a real medium (locally uniform; density ρ_0 and sound speed c_0 at source position)	sound exposure level at a standard reference distance r_ref from a point monopole, placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, that produces the same value of the quantity $\int S(t)\mathrm{d}t$ as would exist in the far field and in a specified direction from the actual source+image if placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium	The value of $10\log_{10}\dfrac{\int S(t)\mathrm{d}t}{p_\mathrm{ref}^2 r_\mathrm{ref}^2 t_\mathrm{ref}}$ that would exist in a specified direction if the same directional source+image were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions, and driven with identical motion of all acoustically active surfaces.
B) finite directional transient source (e.g., sonar transducer) in contact with a partially reflecting surface (represents water-sediment boundary) in an infinite uniform medium (represents water of infinite depth) to one side of the boundary	suggestions invited	The value of $10\log_{10}\dfrac{\int S(t)\mathrm{d}t}{p_\mathrm{ref}^2 r_\mathrm{ref}^2 t_\mathrm{ref}}$ in a specified direction in the infinite uniform medium
C) finite directional transient source (e.g., sonar transducer) in	suggestions invited	The value of $10\log_{10}\dfrac{\int S(t)\mathrm{d}t}{p_\mathrm{ref}^2 r_\mathrm{ref}^2 t_\mathrm{ref}}$ that would exist in a specified

contact with a partially reflecting surface (represents water-sediment boundary) in an infinite uniform medium (density ρ_0 and sound speed c_0; represents water of infinite depth) to one side of the boundary		direction if the same directional source+partially reflecting boundary were placed in a lossless uniform medium of density ρ_0 and sound speed c_0 and extending to infinity in all directions away from the boundary, and driven with identical motion of all acoustically active surfaces, including all parts of the partially reflecting boundary.

B.6 Applicability matrix

Table 22 introduces six types of sources, and for each lists those definitions introduced so far that are applicable to that source, indicated by the letter "Y" and pale green shading. The use of the letter "N" does not necessarily mean that the definition cannot be generalised to make it applicable to that source, but that the definition as presently worded is not applicable. For all types of source, except for the pile driver in shallow water, there is at least one applicable definition.

Table 22 Applicability of source level definitions to various sources.

example application	**sonar**	**air gun**	**explosion**	**pile driver in deep water**	**pile driver in shallow water**	**rain or wind noise**	**surface ship**
source level	Y	N	N	N	N	N	Y
dipole source level	Y	N	N	N	N	N	Y
energy source level	Y	Y	Y	N	N	N	N
energy baffled source level	Y	Y	Y	Y	N	N	N
peak pressure source level	Y	Y	N	N	N	N	N
peak pressure dipole source level	Y	Y	N	N	N	N	N
areic dipole source level	N	N	N	N	N	Y	N

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