UNDERWATER ACOUSTICS - TASK 3: REPORTING

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

JIP Topic - Sound source characterisation and propagation

E&P SOUND & MARINE LIFE PROGRAMME

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About the E&P Sound & Marine Life Programme

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

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

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

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

Contents

1 List of abbreviations

Abbreviation	Stands for
BIPM	International Bureau of Weights and Measures
CGPM	General Conference on Weights and Measures
CGS	centimetre-gram-second (metric system of units in use prior to the SI)
CIPM	International Committee for Weights and Measures
CSA	Continental Shelf Associates, Inc.
DIS	Draft international standard
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ISQ	International System of Quantities
JIP	E&P Sound and Marine Life Joint Industry Programme
NIST	National Institute of Standards and Technology
psi	pound-force per square inch
rms	root-mean-square
SEL	sound exposure level
SI	International System of Units
SPL	sound pressure level
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
UA-R	E&P Sound and Marine Life JIP Standard: Underwater Acoustics - Reporting (this report)

2 Introduction

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

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

The term “acoustical processing” is used here to mean the conversion from time series (e.g., sound pressure vs. time) to processed metrics such as sound pressure level or sound exposure level. This processing is required to provide metrics that are consistent with one another and with the definitions of ISO 18405:2007 (ISO, 2017), and thus facilitate like with like comparison.

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

This document is a standard for reporting quantities associated with measurements or predictions of underwater sound. It is referred to henceforth as the ‘E&P Sound and Marine Life JIP Standard: Underwater Acoustics – Reporting’, abbreviated ‘UA-R’. The main purpose of UA-R is to provide clear recommendations for reporting acoustical and related quantities in connection with measurements or predictions of underwater sound. Section 3 of UA-R describes the concepts of quantities and their units, introducing those of most relevance to underwater acoustics. The UA-R guidance for reporting the quantities in the appropriate units, largely following that of the International System of Quantities in the form of the international standard ISO/IEC 80000, is provided in Sec. 4.

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

3 Quantities and Units

3.1 Introduction

3.1.1 General remarks

In this chapter we introduce the concepts of quantities and their units.
The concepts of a quantity (e.g., speed) and the unit of that quantity are clearly distinguished by modern standards bodies. If the speed of a car is one hundred kilometres per hour, this can be written in equation form as

$$v = 100\ \mathrm{km/h}, \tag{1}$$

where the symbol v represents the physical quantity (speed), the symbol $\mathrm{km/h}$ represents the unit (one kilometre per hour), and 100 represents the value of the quantity when expressed in this unit. Equation (1) represents a *multiplication* of the number times the unit (one hundred times one kilometre per hour).

$$v = 100\ \times (1\ \mathrm{km/h}) \tag{2}$$

This multiplication can be written more generally

$$Q = N \times U \tag{3}$$

where
Q is a symbol representing a specified *physical quantity*; in this example the speed of the car
U is a symbol representing a specified *unit*; in this example km/h
N is the *numerical value* of the quantity Q when expressed in the unit U; in this example, $N = 100$.

For an example from acoustics, consider that Q represents the physical quantity root-mean-square sound pressure (symbol p_{rms}), whose value is ten pascals.
In other words $Q = p_{\mathrm{rms}}$, $N = 10$, and $U = \mathrm{Pa}$, such that

$$p_{\mathrm{rms}} = 10\ \times (1\ \mathrm{Pa}) = 10\ \mathrm{Pa}. \tag{4}$$

3.1.2 The International System of Quantities (ISQ) and the International System of Units (SI)

The International System of Units (SI), founded in 1960, is the universally recognized system of units on which modern precision engineering is founded (BIPM, 2014). The International System of Quantities (ISQ), developed between 2006 and 2009, is relatively new. The ISQ and SI are formally defined by ISO 80000-1:2009 (ISO, 2009a) as follows:

International System of Quantities
ISQ
system of quantities based on the seven base quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity

International System of Units
SI
system of units, based on the International System of Quantities, their names and symbols, including a series of prefixes and their names and symbols, together with rules for their use, adopted by the General Conference on Weights and Measures (CGPM)

The ISQ is described in Parts 3 to 14 of the fourteen-part standard ISO/IEC 80000, published between 2006 and 2009 (see Table 1). The SI and ISQ are intended to be used together so that the quantities defined in the ISQ (the Q in Eq. (3)) are expressed either in SI units or in units outside the SI but accepted for use with the SI by BIPM (2014). Of the fourteen parts of ISO/IEC 80000, the most relevant to acoustics are Parts 1 (General), 2 (Mathematical signs and symbols to be used in the natural sciences and technology) 3 (Space and time) and 8 (Acoustics).

Table 1: The scope of the fourteen-part ISO/IEC 80000 includes physics, chemistry and information technology. Parts 1, 2, 3 and 8 are of most relevance to acoustics.

reference	name	year	notes
ISO 80000-1 (ISO, 2009a)	General	2009	defines neper and bel; explains “power quantity” and “root-power quantity”; deprecates “field quantity” as a synonym of “root-power quantity”.
ISO 80000-2 (ISO, 2009b)	Mathematical signs and symbols to be used in the natural sciences and technology	2009	defines Fourier transform
ISO 80000-3 (ISO, 2006)	Space and Time	2006	defines level of a field quantity and level of a power quantity; clarifies definitions of neper, bel and decibel as units of level;
ISO 80000-4	Mechanics	2006	
ISO 80000-5	Thermodynamics	2007	
IEC 80000-6	Electromagnetism	2008	
ISO 80000-7	Light	2008	

ISO 80000-8 (ISO, 2007)	Acoustics	2007	defines acoustical quantities
ISO 80000-9	Physical chemistry and molecular physics	2008	
ISO 80000-10	Atomic and nuclear physics	2009	
ISO 80000-11	Characteristic numbers	2008	
ISO 80000-12	Solid state physics	2009	
IEC 80000-13 (IEC, 2008)	Information science and technology	2008	
IEC 80000-14	Telebiometrics related to human physiology	2008	

As a general principle the present Reporting Standard follows BIPM (2014) and ISO/IEC 80000. In other words, quantities of the ISQ are expressed either in SI units or in non-SI units accepted by BIPM (2014) for use with SI units.

3.1.3 *The Roles of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC)*

The fourteen-part standard ISO/IEC 80000 was developed jointly by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC).

Of the fourteen parts, eleven are developed by ISO and three by IEC. In general, standards relating to electrical or electronic technology, e.g., IEC 80000-13:2008 (IEC, 2008), are developed by IEC, while those relating to acoustics and other physical sciences are developed by ISO.

Other standards developed by ISO and IEC of particular relevance are the underwater acoustics terminology standard (ISO, 2017) and two hydrophone calibration standards (IEC, 2006; IEC, 2017).

3.2 Standard functions

The standard ISO 80000-2 (ISO, 2009b) shall be followed for definitions and symbols for standard functions. For example, the symbols $\ln$, $\lg$, lb are used for natural (base e), base 10 and base 2 logarithms, respectively.

3.3 Units

3.3.1 *SI Units*

The International System of Units (SI) is described in a regularly updated brochure published by the International Bureau of Weights and Measures (BIPM), which reports to the International Committee for Weights and Measures (CIPM).
At the time of writing, the latest revision of the brochure is BIPM (2014). All SI units are listed in this brochure and are not repeated here. Selected examples are the kilogram (SI unit of mass, symbol kg), metre (SI unit of distance, symbol m), the

second (SI unit of time, symbol s), the newton (SI unit of force, symbol N), and the pascal (SI unit of pressure, symbol Pa).

SI units is shall be used. SI prefixes may be used in combination with SI units. For example

$$1\ \mu\mathrm{Pa} = 10^{-6}\ \mathrm{Pa}$$
$$1\ \mathrm{cm}^2 = (1\ \mathrm{cm})^2 = 10^{-4}\ \mathrm{m}^2.$$

3.3.2 *Non-SI units accepted by the CIPM for use with the SI*

Some non-SI units are listed in BIPM (2014) as being permitted for use with the SI, even though they are not SI units themselves. These units fall into two main categories, according to whether a conversion to SI units is required.
Use of non-SI units is permitted by the present standard if they are accepted by the CIPM for use with the SI.

3.3.2.1 *Non-SI units accepted for use without conversion*

Units that are in everyday use and whose use is expected to continue indefinitely are listed in Table 2. Use of these units with the SI is permitted by the CIPM (see Table 6 of BIPM (2014).

Table 2: Non-SI units accepted for use with the International System of Units.

name of unit	**symbol**	**value**	**notes**
minute	min	60 s	unit of time (compare unit of angle with the same name)
hour	h	60 min	unit of time
day	d	24 h	unit of time
degree	°	π/180 rad	unit of angle
minute	′	(1/60)°	unit of angle (compare unit of time with the same name)
second	″	(1/60)′	unit of angle (compare unit of time with the same name)
hectare	ha	1 hm^2	100 ha = 1 km^2
litre	L	1 dm^3	1000 L = 1 m^3 The alternative unit symbol l is also permitted by [BIPM (2014]. The symbol L is preferred here over l because l (lower case letter “el”) can be confused with the digit 1, the letter I (upper case letter “i”) or similar. Use 10 mL, not 10 ml to mean ten millilitres.
tonne	t	1 Mg	1 Mg = 1000 kg

3.3.2.2 *Non-SI units accepted for use with the SI if conversion provided, including the decibel*

Other units permitted for use by the CIPM with the SI by specialized interest groups are listed in Table 3. These specialized interest groups include branches of engineering, like acoustics, with a longstanding practice of using the decibel as a unit of level. The units barn (symbol b) and ångström (Å) are also permitted by the

CIPM, but are excluded from Table 3 because they are of little relevance to the present application.

Table 3: Selected non-SI units permitted by the CIPM for use with the SI by specialized interest groups.

name of unit	unit symbol	value	notes
bar	bar	0.1 MPa	
nautical mile	nmi	1852 m	The IEEE standard symbol for nautical mile (see IEEE 260.1-2004 (IEEE, 2004)) is nmi.
knot	kn	1 nmi/h	1 kn = (1852/3600) m/s, or to 7 significant figures 1 kn ≈ 0.514 4444 m/s
neper	Np	1	One neper (1 Np) is the level of a power quantity P when the ratio P / P_0 is equal to e^2, where P_0 is the specified reference value of P. For example, if the mean-square sound pressure is e^2 μPa² and the reference sound pressure is μPa, the sound pressure level is 1 Np.
bel		$(1/2)\ln 10$ Np = 10 dB	One bel is the level of a power quantity P when the ratio P/P_0 is equal to 10, where P_0 is the specified reference value of P. For example, if the mean-square sound pressure is 10 μPa² and the reference sound pressure is μPa, the sound pressure level is 1 bel. The symbol used by BIPM (2014) for the bel is B. In UA-R, the symbol B is reserved instead for the byte, which represents a departure from BIPM (2014). See also decibel (this table) and byte (Table 6). Use 20 dB, not 2 B to mean two bels.
decibel	dB	$(1/20)\ln 10$ Np	One decibel (1 dB) is the level of a power quantity P when the ratio P/P_0 is equal to $10^{1/10}$, where P_0 is the specified reference value of P. For example, if the mean-square sound pressure is $10^{1/10}$ μPa² and the reference sound pressure is μPa², the sound pressure level is 1 dB. 1 dB ≈ 0.115 1293 Np Use 0.01 dB, not 1 mB to mean one thousandth of a bel.

One final group of units that is permitted by the CIPM for use with the SI is the set of centimetre-gram-second (CGS) units (BIPM, 2014). Before 1969, one dyne per square centimetre (the CGS unit of pressure, symbol 1 dyn/cm^2) or, equivalently, one microbar (1 μbar) was the American national standard reference value for sound pressure level in water (ANSI, 1960; Ainslie, 2015). In 1969, ANSI adopted one micropascal (1 μPa) as the American national standard for liquids, including water (ANSI, 1969), and in 1994 this reference sound pressure was adopted internationally (IEC, 1994; Ainslie, 2015). Nevertheless, the reference 1 dyn/cm^2 (= 0.1 Pa) remained in use at least until 1986 (Jacobs and Hall, 1972; Fine and Lenhardt, 1983; Fay and Ream, 1986) making the conversion of relevance.
The numerical value of sound pressure level evaluated with the modern reference value of 1 μPa is precisely 100 dB higher than that evaluated with the (pre 1969) legacy reference value of 1 dyn/cm^2.

3.3.2.3 Summary of all non-SI units permitted by CIPM for use with SI

An overview of all non-SI units permitted by CIPM for use with the SI, in alphabetical order, is provided in Table 4. Where values are reported in these non-SI units, in some cases the CIPM requires the value to be accompanied by a conversion to SI units, as indicated in the column ‘CIPM status’. For example

The distance is 10 nmi (18.52 km)
The ship speed is 10 kn (5.14 m/s)
The measurement duration was 1 h

and not

The distance is 10 nmi
The ship speed is 10 kn

Table 4: All non-SI units permitted by CIPM for use with the International System of Units, in alphabetical order.

name of unit	symbol	CIPM status
ångström	Å	accepted with conversion
bar	bar	accepted with conversion
barn	b	accepted with conversion
bel		accepted with conversion
dalton[1]	Da	accepted for use
day	d	accepted for use
decibel	dB	accepted with conversion
degree	°	accepted for use
dyne	dyn	accepted with conversion
electronvolt	eV	accepted for use
erg	erg	accepted with conversion
gal	Gal	accepted with conversion
gauss	G	accepted with conversion
hectare	ha	accepted for use
hour	h	accepted for use
knot	kn	accepted with conversion
litre	L	accepted for use
maxwell	Mx	accepted with conversion
millimetre of mercury	mmHg	accepted with conversion
minute (unit of time)	min	accepted for use
minute (unit of angle)	′	accepted for use
nautical mile	nmi	accepted with conversion
neper	Np	accepted with conversion
oersted	Oe	accepted with conversion
phot	ph	accepted with conversion
poise	P	accepted with conversion
second (unit of angle)	″	accepted for use
stilb	sb	accepted with conversion
stokes	St	accepted with conversion
tonne	t	accepted for use

3.3.3 *Other non-SI units that are part of the ISQ or defined in ISO 18405*

In this section units are listed that are neither explicitly permitted nor deprecated by BIPM, and are included in the ISQ. These are units of logarithmic frequency intervals and of information technology.
Use of non-SI units is permitted by the present standard if they are part of the ISQ or defined in ISO 18405 (ISO, 2017).

Units of logarithmic frequency interval are listed in Table 5. Of particular interest are the decidecade and one-third octave, as these frequency bands are widely used for acoustical processing.

[1] an alternative symbol to Da for the dalton is u

Table 5: Units of logarithmic frequency interval (frequency level).

unit	**symbol**	**definition**	**numerical value**	**notes**
octave	oct	lb 2	1	exact value (ISO, 2007)
decade	dec	lb 10 oct	3.321 928 oct	correct to 7 significant figures (ISO, 2007)
decidecade	ddec	1/10 dec	0.332 1928 oct	correct to 7 significant figures (ISO, 2017)
one-third octave		1/3 oct	1.003 433 ddec	correct to 7 significant figures (ISO, 2017)

Measurements are recorded on digital storage devices, processed and are transmitted using digital technology. Units of information technology are relevant to any measurement and reporting standard that uses such storage, processing or data transmission. One of the most important units of information technology is the byte, the international standard symbol for which, B, is identical to that for the bel (BIPM, 2014) – see Table 6 below. This conflict can be resolved thanks to three simple observations

- the decibel (symbol dB) is almost invariably used in preference to the bel;
- multiples or sub-multiples of the bel other than the decibel are almost never used;
- the concept of one tenth of a byte is almost never used.

Given that dB is the international standard symbol for the decibel (BIPM, 2014), we can resolve the conflict by allocating all other multiples and sub-multiples to the byte, in other words by reserving dB to mean decibel and avoiding dB for decibyte:

Use 100 mB/s, not 1 dB/s to mean one tenth of a byte per second (i.e., one byte every ten seconds).

Use 10 dB, not 1 B to mean one bel.

Table 6: Units of information technology.

unit	symbol	notes
bit	bit	information storage unit corresponding to a single binary digit The bit may be combined with standard SI (i.e., decimal) multiples to form the kilobit (1 kbit = 1000 bit), megabit (1 Mbit = 1000^2 bit), etc. The bit may be combined with standard IEC binary multiples to form the kibibit (1 Kibit = 1024 bit), mebibit (1 Mibit = 1024^2 bit), etc. See IEC (2008) for details.
byte	B	The byte (1 B := 8 bit) may be combined with standard SI (i.e., decimal) multiples to form the kilobyte (1 kB = 1000 B), megabyte (1 MB = 1000^2 B), etc. The byte may be combined with standard IEC binary multiples to form the kibibyte (1 KiB = 1024 B), mebibyte (1 MiB = 1024^2 B), etc. See IEC (2008) for details.

Recall from Sec. 3.3.3 that the symbol dB is reserved for the decibel. Fortunately there is no need for the decibyte, nor for its exotic siblings the hectobyte, decabyte and centibyte. We do see a need for smaller sub-multiples such as the millibyte (Table 6), especially for the expression of underwater communication rates, which for some applications might be of order of a few millibytes per second. With these considerations in mind Table 7 lists permitted uses of the symbol B and its (decimal) multiples and submultiples. According to UA-R the symbol dB always means decibel and never decibyte.

Table 7: Uses of the symbol B combined with SI prefixes for the byte.

symbol	meaning
YB	yottabyte
ZB	zettabyte
EB	exabyte
PB	petabyte
TB	terabyte
GB	gigabyte
MB	megabyte
kB	kilobyte
hB	-
daB	-
B	byte
dB	-
cB	-
mB	millibyte
μB	microbyte
...	etc

3.3.4 *Non-SI units defined by IEEE Std 260.1*

Use of non-SI units is permitted by the present standard if they are part of the ISQ or defined in either ISO (2017) or IEEE 260.1-2004 (IEEE, 2004), in which case appropriate unit symbols specified by those standards shall be used.

Table 8: Selected non-SI units permitted by IEEE (2004).

unit	symbol	SI equivalent	notes
units of length			
foot	ft	0.3048 m	exact value
inch	in	$2.54\ \mathrm{cm}$	exact value
yard	yd	0.9144 m	exact value
units of area			
square inch	in^2	$6.4516\ \mathrm{cm}^2$	exact value
units of volume			
cubic inch	in^3	$16.387\ 064\ \mathrm{cm}^3$	exact value
Imperial gallon	$\mathrm{gal}_{\mathrm{Imp}}$	4.5461 L	
U.S. gallon	$\mathrm{gal}_{\mathrm{US}}$	3.7854 L	defined as 231 cubic inches
barrel	bbl	158.99 L	"This is the standard barrel used for petroleum and petroleum products. Different standard barrels are used for other commodities" (IEEE, 2004)
units of mass			
avoirdupois pound	lb	$0.453\ 592\ 37\ \mathrm{kg}$	exact value (NIST, 2008, footnote 22)
units of force			
pound-force	lbf	$4.448\ 222\ \mathrm{N}$	correct to 7 significant figures (NIST, 2008) The exact value according to (NIST, 2008, footnote 23) is $g \times 1\ \mathrm{lb}$, with $g = 9.806\ 65\ \frac{\mathrm{m}}{\mathrm{s}^2}$.
dyne	dyn	10 μN	CGS unit of force
units of pressure			
pound-force per square inch (psi)	lbf/in^2	$6894.757\ \mathrm{Pa}$	correct to 7 significant figures (NIST, 2008) The exact value, using the NIST (2008) definition of pound-force (above) is $g \times 1\frac{\mathrm{lb}}{\mathrm{in}^2}$.
dyne per square centimetre	dyn/cm^2	0.1 Pa	

3.3.5 *Summary of compliant units*

Units shall be selected from the following:

- SI units are preferred;
- non-SI units from Table 4 are permitted (converted as appropriate, as indicated by Table 4);
- all other units defined by IEEE, 2004 (always converted – see Table 8 for selected examples).

3.4 Quantities

3.4.1 *Field quantities and power quantities*

Many quantities of interest in acoustics are either field quantities (e.g., sound pressure) or power quantities (e.g., sound intensity). What field quantities and power quantities have in common is that they may be expressed as levels, in decibels. If a quantity is proportional to power or energy then that quantity is a power quantity, whereas if it is the square root of a power quantity it is a field quantity. A quantity whose mean-square value is a power quantity is also a field quantity.

Examples of field quantity (ISO, 2006) are sound pressure, sound pressure spectrum, zero-to-peak sound pressure, sound particle displacement, sound particle velocity and sound particle acceleration. Examples of power quantity (ISO, 2006) are mean-square sound pressure, mean-square sound particle displacement, mean-square sound particle velocity, mean-square sound particle acceleration and time-integrated sound pressure.
A power quantity may be weighted to take account of an animal's hearing sensitivity. Weighting of this kind is usually carried out in the frequency domain, as specified in Ainslie et al. (2017b), by multiplying the power quantity by the (linear) auditory frequency weighting function, $w_{\mathrm{aud}}(f)$. Field quantities may be weighted in the same way, by multiplying instead by the square root of the auditory frequency weighting function.

3.4.2 *Other quantities*

There are many quantities of interest to underwater acoustics that are neither power quantities nor field quantities, nor levels of these. Such quantities include time, mass, area, volume, density, frequency, impedance and many more.

3.4.3 *Logarithmic quantities (levels)*

3.4.3.1 *Level of a field quantity*

The level L_F of a field quantity F is

$$L_F = 20\,\lg\frac{F}{F_0}\ \mathrm{dB}, \tag{5}$$

where the symbol lg is used for $\log_{10}$. This equation reveals a more practical definition of dB as unit of level (ISO, 2006), and in underwater acoustics it is conventional to report levels in this unit. The reference value is essential to infer the value of F from that of L_F. For this reason if ambiguity is to be avoided it is necessary to accompany the value of the level L_F with that of the reference value F_0 (see Sec. 4.2.3).

The bel and neper (see Table 3) are alternative units of level but these units are rarely used in underwater acoustics.

3.4.3.2 *Level of a power quantity*

The level L_P of a power quantity P is

$$L_P = 10\,\mathrm{lg}\frac{P}{P_0}\ \mathrm{dB}. \tag{6}$$

In Eq. (1), P_0 is the reference value.

3.4.3.3 *Frequency level (logarithmic frequency interval)*

The concept of frequency level is introduced by ANSI (2013), entry 3.05, and can be defined using either

$$L_f = \mathrm{lb}\frac{f}{f_0}\ \mathrm{oct}, \tag{7}$$

where the symbol lb is used for $\log_2$, or

$$L_f = \mathrm{lg}\frac{f}{f_0}\ \mathrm{dec}. \tag{8}$$

Use of the octave as a unit implies a base 2 logarithm, while use of the decade as a unit implies a base 10 logarithm.

These frequency levels are logarithmic frequency intervals, and a processing band often used in underwater acoustics is one third of an octave, i.e. 1/3 oct. If 1/3 oct is used as the unit of frequency level, Eq. (7) can be written

$$L_f = 3\,\mathrm{lb}\frac{f}{f_0}\ \left(\frac{1}{3}\mathrm{oct}\right). \tag{9}$$

Also in widespread use is a processing band of one tenth of a decidade (1/10 dec = 1 ddec), giving

$$L_f = 10\,\mathrm{lg}\frac{f}{f_0}\ \mathrm{ddec} \tag{10}$$

These units of frequency level, their precise (ISO) definitions and the relationship between them, are listed in Table 5.

3.5 Symbols and abbreviations

ISO (2009a) distinguishes between symbols and abbreviations. Both are concise representations of quantities or units, but with a different purpose. As a general rule, symbols are used in equations and abbreviations in text. Examples are provided below for selected quantities (Table 9) and units (Table 10).

Table 9: Symbols and abbreviations for selected quantities.

quantity	abbreviation	symbol
sound pressure level	SPL	L_p
sound exposure level	SEL	L_E

Table 10: Symbols and abbreviations for selected units.

unit	abbreviation	symbol
pound-force per square inch	psi	lbf/in^2
cubic centimetre	cc	cm^3
cubic inch	cu in	in^3

3.5.1 *Symbols*

Symbols are used in mathematics to represent a concept in an equation. In Eq. (4), reproduced here as Eq. (11)

$$p_{\mathrm{rms}} = 10 \times (1\ \mathrm{Pa}) = 10\ \mathrm{Pa}, \tag{11}$$

p_{rms} and Pa are, respectively, *symbols* representing the rms sound pressure (the quantity) and the pascal (the unit in which the quantity is expressed). The number 10 is the numerical value of p_{rms} when expressed in pascals.

Without changing the value of p_{rms} one can change the unit to $\mu\mathrm{Pa}$, in which case $N = 10^7$ and then

$$p_{\mathrm{rms}} = 10^7 \times (1\ \mu\mathrm{Pa}) = 10^7\ \mu\mathrm{Pa}. \tag{12}$$

Substituting Eq. (12) in Eq. (6) (with $P = p_{\mathrm{rms}}^2$ and $P_0 = p_0^2$, where p_0 is the reference sound pressure $p_0 = 1\ \mu\mathrm{Pa}$), the rms sound pressure may be expressed as sound pressure level, which is the level of the power quantity mean-square sound pressure ($\overline{p^2} = p_{\mathrm{rms}}^2$)

$$L_p = 10 \lg \frac{p_{\mathrm{rms}}^2}{p_0^2}\ \mathrm{dB}. \tag{13}$$

In Eq. (13), L_p is the symbol for sound pressure level.

3.5.2 *Abbreviations*

An abbreviation is a shortened version of a longer word or phrase that is used to replace that word or phrase in text, thereby shortening the text. Widely used abbreviations in underwater acoustics are SPL for sound pressure level and SEL for sound exposure level. Also used in the previous section is “rms”, used as abbreviation for “root-mean-square”.

4 Reporting

4.1 General

As a general principle, quantities should be reported either in SI units, providing conversions to other units where appropriate, or in units of the ISQ. The ISQ provides clear guidelines for reporting quantities in SI units or units of the ISQ permitted for use with the SI. These guidelines are generally to be followed.

Exceptions to the above general principle are permitted by UA-R if they are compliant with the IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units), IEEE Std 260.1™-2004 (IEEE, 2004). That standard defines customary inch-pound units such as the inch, pound, and pound-force per square inch (psi). Use of such legacy units is permitted by UA-R, even if they are deprecated by the CIPM. Where such units are used the standard IEEE (2004) shall be followed for their names and symbols, and a conversion shall be provided to SI units.

4.2 Values of quantities

4.2.1 Field quantities and power quantities

4.2.1.1 Use of SI units

Field quantities and power quantities are always expressed in SI units. The BIPM brochure (BIPM, 2014) and ISO (2009a) are followed for reporting quantities in SI units.

4.2.1.2 Example

The root-mean-square sound pressure (symbol p_{rms}) is an example of a field quantity. For the example of Sec. 3.1.1 its value is ten pascals, which may be written

$$p_{\mathrm{rms}} = 10\ \mathrm{Pa}$$

or

$$p_{\mathrm{rms}} = 10^7\ \mathrm{\mu Pa}.$$

Notice the subscript “rms” is upright (not italic) because it is an abbreviation (for “root-mean-square”). The $\mathrm{\mu}$ and Pa in $\mathrm{\mu Pa}$ are also upright as they are symbols representing a constant prefix and a unit, respectively.

4.2.1.3 Time and frequency weighting

Both power quantities and field quantities may be filtered by applying various filter functions, such as Hann, Hamming or Tukey windows, whether in the time domain (Harris, 1978) or frequency domain (Ainslie, 2010, p264). Sometimes a filter is applied to account for the frequency dependence or time response of animals’ hearing sensitivity (Southall et al., 2007; NMFS, 2016) – see also Sec. 6.1 of Ainslie et al. (2017b). Such filters shall be fully specified. In all cases the frequency band and time duration of the filter shall be specified. Other information germane to a particular type of filter such as the height offset of a Hamming window or the edge width of a Tukey window.

As an example of auditory frequency weighting, if the abbreviation “M-LF” has been introduced to denote M-weighting for low-frequency cetaceans, and the corresponding weighted sound exposure is

$$E_{p,\mathrm{M-LF}} = 10^5\ \mathrm{Pa}^2\ \mathrm{s}$$

not

$$E_p = 10^5\ \mathrm{Pa}^2\ \mathrm{s}\ (\mathrm{M-LF})$$

4.2.2 *Other linear quantities*

Rules for reporting quantities in SI units in general are the same as those for field quantities and power quantities in Sec. 4.2.1. Conversions to non-SI units are permitted.

UA-R accepts that units deprecated by CIPM and other standards bodies have been used, and are likely to continue to be used, making it desirable to provide conversions for those in most common use. One can therefore envisage situations in which certain units are used, even though deprecated. In this situation, IEEE (2004) shall be followed and a justification for the use and a conversion to SI shall be provided.

The vessel was travelling at a speed of 10.3 m/s (20 kn).
The volume of the airgun is 40 in^3 (655 cm^3).
The volume of the airgun is 6.55 L (40 in^3).
The firing pressure is 2000 lbf/in^2 (13.8 MPa).

not

The vessel was travelling at a speed of 20 kn.
The vessel was travelling at a speed of 10.3 m/s (20 kt).
The volume of the airgun is 40 cu in.
The firing pressure is 2000 lbf/in^2.
The firing pressure is 2000 psi.
The firing pressure is 13.8 MPa (2000 psi).

4.2.3 *Levels of field and power quantities*

4.2.3.1 *Reporting levels according to IEC 60027-3:2002*

For reporting levels IEC 60027-3:2002 (IEC, 2002) shall be followed, with stated exceptions. The level of a power quantity is expressed in decibels (dB). The level of a field quantity may be expressed in decibels (dB) or nepers (Np). The reference value of shall be stated. The choice of reference value shall follow ISO 1683 (ISO, 2015) and ISO 18405.

The sound pressure level (SPL) corresponding to an rms sound pressure of 10 Pa, for a reference sound pressure of 1 μPa, may be written

$$L_p(\mathrm{re}\ 1\ \mu\mathrm{Pa}) = 140\ \mathrm{dB}$$
$$L_{p/(1\ \mu\mathrm{Pa})} = 140\ \mathrm{dB}$$
$$L_p = 140\ \mathrm{dB}\ (1\ \mu\mathrm{Pa})$$

If the exposure duration is 100 s, the corresponding sound exposure level (SEL) relative to 1 μPa² s is 160 dB. This may be written

$$L_E(\text{re } 1\ \mu\text{Pa}^2\ \text{s}) = 160\ \text{dB}$$
$$L_{E/(1\ \mu\text{Pa}^2\ \text{s})} = 160\ \text{dB}$$
$$L_E(1\ \mu\text{Pa}^2\ \text{s}) = 160\ \text{dB}$$

If the numerical value of the reference quantity is 1 (as in $p_{\text{ref}} = 1\ \mu\text{Pa}$) it may be omitted. For example

$$L_{p/\mu\text{Pa}} = 140\ \text{dB}$$
$$L_{E/(\mu\text{Pa}^2\ \text{s})} = 160\ \text{dB}$$

Attachments to the decibel symbol are not permitted

$$L_p(\text{re } 1\ \mu\text{Pa}) = 140\ \text{dB}_{\text{rms}}$$
$$L_p(\text{re } 1\ \mu\text{Pa}) = 140\ \text{dBSPL}$$
$$L_p(\text{re } 1\ \mu\text{Pa}) = 120\ \text{dBA}$$
$$L_p(\text{re } 1\ \mu\text{Pa}) = 140\ \text{dB}_{\text{rms}}$$
$$L_E(\text{re } 1\ \mu\text{Pa}^2\ \text{s}) = 160\ \text{dB}_{\text{SEL}}$$

$$L = 150\ \text{dB}_{\text{peak}}$$
$$L_p = 140\ \text{dB}(1\ \mu\text{Pa})$$

where the last example is not permitted because of the absence of a space between the dB symbol and the reference value.

The purpose of this rule is to avoid ambiguity by establishing a clear distinction between a physical quantity (Q) and the unit in which that quantity is expressed (U). It is a general SI rule and applies to all unit symbols. Unit modifiers are never permitted (BIPM, 2014):

> *Just as the quantity symbol should not imply any particular choice of unit, the unit symbol should not be used to provide specific information about the quantity, and should never be the sole source of information on the quantity. Units are never qualified by further information about the nature of the quantity; any extra information on the nature of the quantity should be attached to the quantity symbol and not to the unit symbol.*

Abbreviations are used in text. Symbols are used in equations

The SPL relative to $1\ \mu\text{Pa}$ is equal to 140 dB.
$$L_p = 140\ \text{dB re } 1\ \mu\text{Pa},$$

not

$$\text{SPL} = 140\ \text{dB re } 1\ \mu\text{Pa}.$$

The rms sound pressure is 10 Pa
The height above sea level is 10 m

not

The sound pressure is 10 Pa_{rms}
The height is 10 masl.

4.2.3.2 Exceptions to IEC 60027-3:2002

Though not compliant with IEC 60027-3:2002 (IEC, 2002), levels may be reported in the form

$$L_p = 140 \text{ dB re } 1\ \mu\text{Pa},$$

which is interpreted as the level of a field quantity (the root-mean-square sound pressure, p_{rms})

$$20 \lg \frac{p_{\text{rms}}}{1\ \mu\text{Pa}} \text{ dB} = 140 \text{ dB}. \tag{14}$$

Alternatively the same value may be written

$$L_p = 140 \text{ dB re } 1\ \mu\text{Pa}^2\ ,$$

which is interpreted as the level of a power quantity (the mean-square sound pressure, p_{rms}^2)

$$10 \lg \frac{p_{\text{rms}}^2}{1\ \mu\text{Pa}^2} \text{ dB} = 140 \text{ dB} \tag{15}$$

Other terms like sound exposure level may also be written in these two alternative forms, either as the level of a power quantity

$$L_E = 160 \text{ dB re } 1\ \mu\text{Pa}^2\text{s}$$

or as the level of a field quantity

$$L_E = 160 \text{ dB re } 1\ \mu\text{Pa s}^{\frac{1}{2}}$$

A mid-dot may be used instead of a space to separate unit symbols

$$L_E = 160 \text{ dB re } 1\ \mu\text{Pa}^2{\cdot}\text{s}$$

but not a hyphen, nor a full stop (period)

$$L_E = 160 \text{ dB re } 1\ \mu\text{Pa}^2\text{-s}$$
$$L_E = 160 \text{ dB re } 1\ \mu\text{Pa}^2\text{.s}$$

Other examples of reference values for field quantities and power quantities are listed in Table 12. Of particular interest is the reference value of source factor, equal to 1 μPa^2 m^2, because of confusion arising from reporting the level of this quantity, the source level. The value of source level is often written with a reference value of “1 μPa at 1 m” or “1 μPa @ 1 m”, giving the misleading impression that source level is the sound pressure level at one metre from the source. Following ISO (2017), the correct reference value for source level is either the reference value of the power quantity source factor (1 μPa^2 m^2) or that of the corresponding field quantity, root source factor (1 μPa m). In other words, values of source level shall be reported in the form

$$L_S = 200 \text{ dB re } 1 \text{ μPa}^2 \text{ m}^2$$

or

$$L_S = 200 \text{ dB re } 1 \text{ μPa m},$$

and not

$$L_S = 200 \text{ dB re } 1 \text{ μPa @ } 1 \text{ m}.$$

If the level is weighted (i.e., it is the level of a weighted field or power quantity), this may be denoted by the subscript “w” or by some other indication, such as “M-LF” for low-frequency M-weighting. Whatever notation is used, the weighting function shall be specified.

If the abbreviation “N16-PP” has been introduced to denote the weighting of the 2016 NOAA Guidance (NMFS, 2016) for phocid pinnipeds, and the corresponding weighted sound exposure $E_{p,\mathrm{N16-PP}}$ is equal to 10^6 Pa^2 s, the corresponding weighted sound exposure level (SEL) relative to 1 μPa^2 s is 180 dB, which may be written

$$L_{E/(1\ \mu\mathrm{Pa}^2\ \mathrm{s}),\mathrm{N16-PP}} = 180 \text{ dB}$$

or

$$L_{E,\mathrm{N16-PP}} = 180 \text{ dB re } 1 \text{ μPa}^2 \text{ s}$$

and not (only the reference value is permitted after the unit symbol “dB”)

$$L_E = 180 \text{ dB re } 1 \text{ μPa}^2 \text{ s (N16} - \text{PP)}$$

or

$$L_E = 180 \text{ dB re } 1 \text{ μPa}^2 \text{ s (N16} - \text{PP)}.$$

Suggested abbreviations to denote the weighting functions of Southall et al. (2007) (M-weighting) and (NMFS, 2016). It is recommended to include the year of publication in the abbreviation to facilitate unambiguous denomination in the event of possible future updates.

Table 11: Suggested abbreviations to denote the weighting functions of Southall et al. (2007) (“M-weighting”) and NMFS (2016).

functional hearing group	**Southall et al. (2007)**	**NMFS (2016)**
low-frequency cetaceans	M07-LF	N16-LF
mid-frequency cetaceans	M07-MF	N16-MF
high-frequency cetaceans	M07-HF	N16-HF
phocid pinnipeds in water	M07-PW	N16-PP
otariid pinnipeds in water	M07-PW	N16-OP

If no ambiguity results from doing so, the year may be omitted. For example, “N16-HF” (or “M07-PW”) may be abbreviated “N-HF” or (“M-PW”) if it is clear from the context that the weighting function is that of NMFS (2016) (or Southall et al. (2007)).

Table 12: Power quantities, their corresponding field quantities (or root-power quantities), and their reference values (table reproduced from ISO (2017)).

Power quantity (P)	**Reference value** (P_0)	**Corresponding root-power quantity** ($F_{\mathrm{rp}} = P^{1/2}$)	**Reference value** ($F_0 = P_0{}^{1/2}$)
Mean-square sound pressure	1 μPa^2	Root-mean-square sound pressure	1 μPa
Mean-square sound particle displacement	1 pm^2	Root-mean-square sound particle displacement	1 pm
Mean-square sound particle velocity	1 nm^2/s^2	Root-mean-square sound particle velocity	1 nm/s
Mean-square sound particle acceleration	1 μm^2/s^4	Root-mean-square sound particle acceleration	1 μm/s^2
Sound exposure	1 μPa^2 s	Root sound exposure	1 μPa s$^{1/2}$
Sound power	1 pW	Root sound power	1 pW$^{1/2}$
Sound energy	1 pJ	Root sound energy	1 pJ$^{1/2}$
Source factor	1 μPa^2 m^2	Root source factor	1 μPa m
Propagation factor	1 m^2	Root propagation factor	1 m

4.2.4 *Logarithmic frequency bands*

When reporting levels such as SPL or SEL in logarithmic frequency bands, base 10 bands shall be used. IEC 61260-1:2014 (IEC, 2014) shall be followed for the centre frequencies of these logarithmic frequency bands. The resulting centre frequencies are determined by integer values of the index n according to

$$f_{\mathrm{c},n} = 10^{\frac{n}{10}}\,\mathrm{kHz}. \tag{16}$$

Each decidecade band runs from a twentieth of a decade below to a twentieth of a decade above the centre frequency, such that

$$f_{\mathrm{min},n} = f_{\mathrm{c},n}\,10^{-\frac{1}{20}} \tag{17}$$

$$f_{\mathrm{max},n} = f_{\mathrm{c},n}\,10^{+\frac{1}{20}}. \tag{18}$$

The centre frequencies and upper and lower frequency limits corresponding to values of n between -30 and +30 are listed in Table 13. The decidecade bands with centre frequencies determined by Eq. (16) are sometimes referred to as “one-third octave bands”. This practice is deprecated.

Table 13: Decidecade frequency bands, as defined by IEC (2014), with nominal centre frequencies between 1 Hz and 1 MHz. Selected parameters of bands with index -16 to +13 (shaded) are shown in Table 1 of Ainslie et al. (2017b).

index n	lower limit $f_{\mathrm{min},n}$ /Hz	centre frequency $f_{\mathrm{c},n}$ /Hz	upper limit $f_{\mathrm{max},n}$ /Hz
-30	0.891251	1	1.122018
-29	1.122018	1.258925	1.412538
-28	1.412538	1.584893	1.778279
-27	1.778279	1.995262	2.238721
-26	2.238721	2.511886	2.818383
-25	2.818383	3.162278	3.548134
-24	3.548134	3.981072	4.466836
-23	4.466836	5.011872	5.623413
-22	5.623413	6.309573	7.079458
-21	7.079458	7.943282	8.912509
-20	8.912509	10	11.22018
-19	11.22018	12.58925	14.12538
-18	14.12538	15.84893	17.78279
-17	17.78279	19.95262	22.38721
-16	22.38721	25.11886	28.18383
-15	28.18383	31.62278	35.48134
-14	35.48134	39.81072	44.66836
-13	44.66836	50.11872	56.23413
-12	56.23413	63.09573	70.79458
-11	70.79458	79.43282	89.12509
-10	89.12509	100	112.2018
-9	112.2018	125.8925	141.2538
-8	141.2538	158.4893	177.8279
-7	177.8279	199.5262	223.8721
-6	223.8721	251.1886	281.8383
-5	281.8383	316.2278	354.8134
-4	354.8134	398.1072	446.6836
-3	446.6836	501.1872	562.3413
-2	562.3413	630.9573	707.9458
-1	707.9458	794.3282	891.2509
0	891.2509	1000	1122.018
1	1122.018	1258.925	1412.538
2	1412.538	1584.893	1778.279
3	1778.279	1995.262	2238.721
4	2238.721	2511.886	2818.383
5	2818.383	3162.278	3548.134
6	3548.134	3981.072	4466.836
7	4466.836	5011.872	5623.413
8	5623.413	6309.573	7079.458
9	7079.458	7943.282	8912.509
10	8912.509	10000	11220.18
11	11220.18	12589.25	14125.38

12	14125.38	15848.93	17782.79
13	17782.79	19952.62	22387.21
14	22387.21	25118.86	28183.83
15	28183.83	31622.78	35481.34
16	35481.34	39810.72	44668.36
17	44668.36	50118.72	56234.13
18	56234.13	63095.73	70794.58
19	70794.58	79432.82	89125.09
20	89125.09	100000	112201.8
21	112201.8	125892.5	141253.8
22	141253.8	158489.3	177827.9
23	177827.9	199526.2	223872.1
24	223872.1	251188.6	281838.3
25	281838.3	316227.8	354813.4
26	354813.4	398107.2	446683.6
27	446683.6	501187.2	562341.3
28	562341.3	630957.3	707945.8
29	707945.8	794328.2	891250.9
30	891250.9	1000000	1122018

4.3 Labelling graphs and tables

Graphs and tables are special cases. They are used to convey information concisely (short), and it is important that this information also be conveyed unambiguously (long). ISO (2009a) has rules to deal with these conflicting requirements, which permit an abbreviated form for use in tables and graphs by dividing Eq. (3) through by the unit U, resulting in

$$Q/U = N \tag{19}$$

Dividing through by the unit, the examples $p_{\mathrm{rms}} = 10\ \mathrm{Pa}$ and $L_{p/\mu\mathrm{Pa}} = 140\ \mathrm{dB}$ become

$$p_{\mathrm{rms}}/\mathrm{Pa} = 10$$

and

$$L_{p/\mu\mathrm{Pa}}/\mathrm{dB} = 140$$

and this is the format prescribed by ISO (2009a) for use in tables (Table 14) and graphs (Figure 1).

Table 14: Reporting sound pressure level (SPL) and root-mean-square sound pressure in a table.

distance x/m	**rms sound pressure** $p_{\mathrm{rms}}(x)/\mathrm{Pa}$	**sound pressure level (SPL)** $L_{p/\mu\mathrm{Pa}}(x)/\mathrm{dB}$
1	10	140.0
2	3	129.5
3	1	120.0
4	0.4	112.0
5	0.1	100.0
6	0.01	80.0
7	0.03	89.5
8	0.04	92.0
9	0.001	60.0

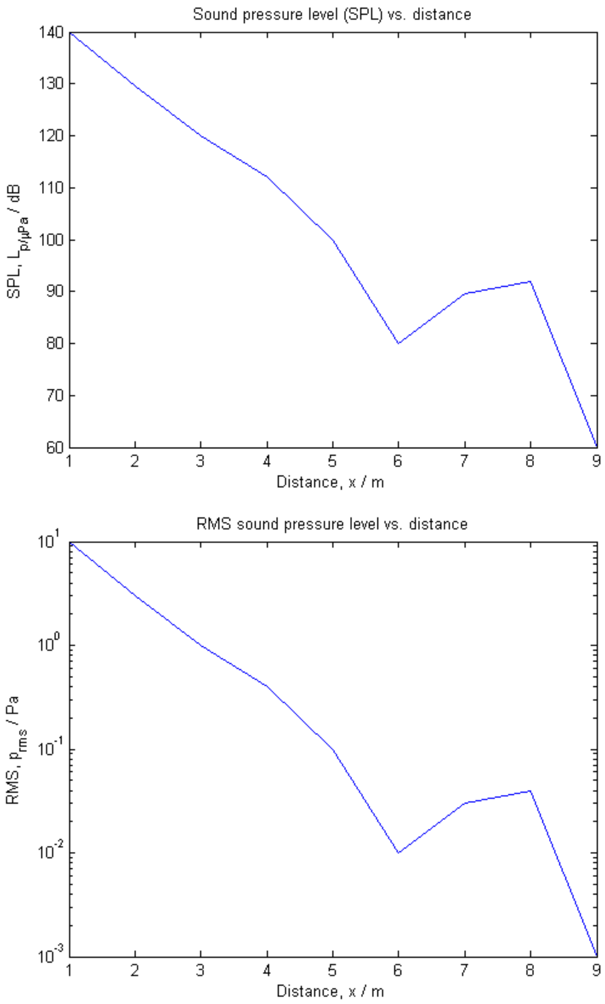

Figure 1 Reporting sound pressure level ($L_{p/\mu\mathrm{Pa}}$) and root-mean-square sound pressure (p_{rms}) in a graph.

4.4 Italicization of symbols and abbreviations

Italicization is used by ISO/IEC 80000 to convey information about the nature of the quantity represented by a symbol, depending on whether it is typeset in an upright (roman) or italic font. By contrast, unless the text is italicized for some other reason, abbreviations are always upright and carry no such information.

Symbols for variables, such as sound pressure (p) or level (L) are italic.
Symbols for physical constants, such as the speed of light (c), Planck's constant (h) and electron charge (e) are italic.
Symbols for mathematical constants, such as pi (π), Euler's number (e) and the imaginary unit (i) are upright.
Symbols for units such as micropascal (μPa), and decibel (dB) are upright.

$$L_p = 10 \lg \frac{p_{\mathrm{rms}}^2}{p_0^2} \mathrm{~dB}$$

but not

$$L_p = 10 \lg \frac{p_{rms}^2}{p_0^2} \mathrm{~dB}$$

$$L_{\mathrm{p}} = 10 \lg \frac{p_{\mathrm{rms}}^2}{p_0^2} \mathrm{~dB}$$

5 Summary

A standardized reporting format enables information to be reported concisely and interpreted unambiguously, thereby reducing confusion. With stated exceptions, the International System of Quantities (ISO/IEC 80000, abbreviated “ISQ”) is followed. Specifically, reporting of quantities and units is based on the ISQ (ISO, 2009a), which in turn is based on BIPM (2014). Exceptions are permitted following the rules of Sec. 4.2.3.2 (for levels) and of IEEE (2004) (for unit symbols outside the ISQ).

Definitions of quantities and units are based on ISO (2017), which in turn is based on the ISQ. Quantities and units outside the ISQ are permitted where defined by IEEE (2004). The following specific standards apply in the following order of decreasing precedence:

- this standard (permitting exceptions per IEEE (2004));
- ISO 18405:2017 (ISO, 2017);
- ISO 80000-8:2007 (ISO, 2007);
- ISO 80000-3:2006 (ISO, 2006);
- ISO 80000-2:2009 (ISO, 2009b);
- ISO 80000-1:2009 (ISO (2009a);
- BIPM (2014).

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