A Terminology Standard for Underwater Acoustics and the Benefits of International Standardization

Michael A. Ainslie, Michele B. Halvorsen, and Stephen P. Robinson

***Abstract*—Applications of underwater acoustics include sonar, communication, geophysical imaging, acoustical oceanography, and bioacoustics. Specialists typically work with little interdisciplinary interaction, and the terminology they employ has evolved separately in each discipline, to the point that transdisciplinary misunderstandings are common. Furthermore, increasing societal concern about possible detrimental effects of underwater noise on aquatic animals has led national and international regulators to require monitoring of underwater noise, with a consequent need for interdisciplinary harmonization of terminology. By adopting a common language, we facilitate the effective communication of concepts and information in underwater acoustics, whether for research, technology, or regulation. In the words of William H. Taft, "Don't write so that you can be understood, write so that you can't be misunderstood." Clear definitions of widely used terms are needed, such as those used for the characterization of sound fields (e.g., "soundscape" and "ambient noise"), sound sources ("source level" and "source waveform"), sound propagation ("transmission loss" and "propagation loss"), and sound reception ("hearing threshold" and "frequency weighting function"). Terms that are used synonymously in one application have different meanings in another (examples include "hearing threshold" versus "detection threshold" and "transmission loss" versus "propagation loss"). Distinct definitions for these and many other acoustic terms are provided in a standard published in April 2017 by the International Organization for Standardization, ISO 18405. This article summarizes ISO 18405 and the process that led to the published definitions, including the reasons for omitting some terms.**

***Index Terms*—Acoustical oceanographic, marine bioacoustics, sonar, standard terminology.**

NOMENCLATURE

Symbol	Description
a	Low-frequency weighting function exponent.
A	Power quantity or ratio of power quantities in (18).
A_0	Reference value of the quantity represented by the symbol A.
b	High-frequency weighting function exponent.
B	Power quantity or ratio of power quantities in (19).
B_0	Reference value of the quantity represented by the symbol B.
B_{ac}	Auditory critical bandwidth.
c	Speed of sound.
E	Sound exposure.
E_0	Reference value of time-integrated squared sound pressure (1 μPa^2 s).
E_{w}	Weighted sound exposure.
E_Ω	Far-field energy per unit solid angle.
f	Frequency.
f_0	Reference value of frequency (1 Hz).
f_1	Denominator of the frequency ratio in (25).
f_2	Numerator of the frequency ratio in (25).
f_{hi}	Higher auditory roll-off frequency.
f_{lo}	Lower auditory roll-off frequency.
F_{S}	Source factor.
$F_{\mathrm{S},E}$	Energy source factor.
G	LFR; Logarithmic frequency ratio.
H	Sound pressure transfer function.
I_{bs}	Far-field backscattered intensity at distance r from a scatterer.
I_{in}	Intensity of incident plane wave.
I_{out}	Far-field scattered intensity at distance r from a scatterer.
I_0	Reference value of sound intensity (1 pW/m^2).
L	Level.
L_E	SEL; Sound exposure level.
$L_{E,f}$	Sound exposure spectral density level.
$L_{E,\mathrm{w}}$	Weighted sound exposure level.
L_p	SPL (Lrms); Sound pressure level (or mean-square sound pressure level).
$L_{p,\mathrm{bHT}}$	Sound pressure level of the behavioral hearing threshold.
$L_{p,\mathrm{n}}$	Sound pressure level of the noise.
$L_{p,\mathrm{s}}$	Sound pressure level of the signal.
L_P	Level of the power quantity P.
$L_{p,0-\mathrm{pk}}$	Lpk; Peak sound pressure level.
$L_{p,f}$	Mean-square sound pressure spectral density level.
L_Q	Level of the quantity Q.
L_{S}	SL; Source level.
$L_{\mathrm{S},E}$	ESL; Energy source level.
$L_{p,\mathrm{TE}}$	Target echo sound pressure level.
N_{PL}	PL; Propagation loss.
$N_{\mathrm{PL,E}}$	EPL; Sound exposure propagation loss (energy propagation loss).
$N_{\mathrm{PL,Rx}}$	Propagation loss from target to receiver.

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Michael A. Ainslie is with JASCO Applied Sciences (Deutschland) GmbH, 65760 Eschborn, Germany (e-mail: michael.ainslie@jasco.com).

Michele B. Halvorsen was with CSA Ocean Sciences, Stuart, FL 34997, USA. She is now with the Center for Acoustic Research and Education and the School of Marine Science and Ocean Engineering, University of New Hampshire, Durham, NH 03824 USA (e-mail: michele.halvorsen@unh.edu).

Stephen P. Robinson is with the National Physical Laboratory, Teddington TW11 0LW, U.K. (e-mail: stephen.robinson@npl.co.uk).

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$N_{\mathrm{PL,Tx}}$	Propagation loss from transmitter to target.
N_{TS}	TS; Target strength.
$N_{\mathrm{TS,eq}}$	eqTS; Equivalent target strength.
p	Sound pressure.
p_0	Reference value of sound pressure (1 μPa).
p_{pk}	Peak sound pressure.
$p_{\mathrm{pk,c}}$	Peak compressional pressure.
$p_{\mathrm{pk-pk}}$	Peak to peak sound pressure.
$p_{\mathrm{pk,r}}$	Peak rarefactional pressure.
p_{rms}	Root-mean-square sound pressure.
p_{w}	Weighted sound pressure.
P	Sound pressure spectrum.
P_{w}	Weighted sound pressure spectrum.
Q	Quantity.
Q_0	Reference value of the quantity Q.
Q_P	Power quantity.
$Q_{P,0}$	Reference value of the power quantity Q_P.
r	Distance from source or scatterer.
R_{c}	CR; Critical ratio.
R_{sn}	Signal-to-noise ratio.
$R_{\mathrm{sn},50}$	Signal-to-noise ratio when the probability of detecting a signal in a noisy background is 50%.
s	Source waveform.
S	Source spectrum.
t	Time.
T	Integration interval.
t_0	Reference value of time (1 s).
w_{aud}	Auditory frequency weighting function.
$w_{\mathrm{aud,M}}$	Auditory frequency weighting function for M-weighting.
W_{aud}	Logarithmic auditory frequency weighting function.
W_{Ω}	Far-field radiant intensity.
$\boldsymbol{x}$	Position vector.
$\boldsymbol{x}_1$	First of two position vectors in the definition of transmission loss.
$\boldsymbol{x}_2$	Second of two position vectors in the definition of transmission loss.
ΔE	Contribution to sound exposure in frequency band Δf.
Δf	Bandwidth.
ΔL_{DT}	DT; Detection threshold.
ΔL_{PG}	PG; Processing gain.
ΔL_{SE}	SE; Signal excess.
ΔL_{TL}	TL; Transmission loss.
$\Delta\overline{p^2}$	Contribution to mean-square sound pressure in frequency band Δf.
α	Radius of rigid sphere.
β	Base of the logarithm in the definition of L_Q.
ϵ	Dimensionless parameter given by (68).
Λ_A	Logarithmic ratio given by (18).
Λ_B	Logarithmic ratio given by (19).
ν	Frequency at which the auditory frequency weighting function reaches a maximum.
ν_{M}	Value of ν for M-weighting.
ρ	Density.
σ_{bs}	Backscattering cross section.
σ_{Ω}	Differential scattering cross section.
$\sigma_{\Omega,\mathrm{bs}}$	Differential backscattering cross section.

I. Introduction

A. *Motivation and Objectives*

THROUGH the millennia, there have been thinkers like Confucius who have advocated for clarity in language to prevent misunderstandings and minimize confusion resulting from ambiguity (Box 1). While a clear language seems a self-evident prerequisite for effective communication, somehow the field of underwater acoustics developed for 100 years without one [1].

By adopting a common language, we facilitate the effective communication of concepts and information in underwater acoustics, whether for research, technology, or regulation. Clear definitions of widely used terms are needed, such as those used for the characterization of sound fields (e.g., soundscape and ambient noise), sound sources [source level (SL) and source waveform], sound propagation [transmission loss (TL) and propagation loss (PL)], and sound reception (hearing threshold and frequency weighting function).

The purposes of this article are to describe the development and contents of ISO 18405, including the reasons for omitting some terms, and to clarify the implications of selected definitions and conventions.

B. *Standardization of Acoustical Terminology*

The first steps toward standardization in acoustics were taken by the Acoustical Society of America (ASA) by establishing a Committee on Acoustical Standardization in December 1929. This committee, chaired by H. A. Frederick, published a report consisting of 38 pages of definitions in January 1931 [5], [6]. A standardization project, Acoustical Measurement and Terminology, was subsequently proposed to the American Standards Association (AStA), now the American National Standards Institute (ANSI). The ensuing project included a terminology subcommittee, chaired by C. F. Wiebusch. This subcommittee, in collaboration with a music subcommittee (chaired by P. H. Bilhuber), produced a tentative American standard in February 1936 [7] and the American Standard Acoustical Terminology in 1942 [8].

Following these early developments in the USA, in 1947, the International Organization for Standardization (ISO) established its own acoustics technical committee (TC 43 Acoustics), of which the underwater acoustics subcommittee (ISO/TC 43/SC 3; see [9]) was created 64 years later in 2011.

1) History, 1942–2010: The American Standard Acoustical Terminology Z24.1-1942 [8] defined selected fundamental concepts (e.g., "sound" and "noise"), quantities ("pressure level" and "loudness"), and units ("decibel" and "octave"). AStA Z24.1-1942 [10] is the first national standard known to the authors to include underwater acoustical terminology. The underwater acoustics section defines concepts (e.g., "cavitation") and objects (e.g., "hydrophone") but not quantities. ANSI S1.1-1960 [11] standardized the definitions of "target strength (TS)" and "sonar dome insertion loss," for the first time assigning a meaning to quantities specific to underwater acoustics.

Applications of underwater acoustics include sonar, communication, geophysical imaging, acoustical oceanography, and

BOX 1

Confucius (Chinese teacher, philosopher 551–479 BC):

If language is not correct, then what is said is not what is meant; if what is said is not what is meant, then what must be done remains undone; if this remains undone, morals and art will deteriorate; if justice goes astray, the people will stand about in helpless confusion. Hence there must be no arbitrariness in what is said. This matters above everything.

Source: Williams [2]
Image: By Wu Daozi, 685–758, Tang Dynasty.
https://commons.wikimedia.org/w/index.php?curid=857482

Étienne Bonnot **de Condillac** (French philosopher 1714–1780):

every science requires special language because every science has its own ideas … it seems that one ought to begin by composing this language, but people begin by speaking and writing, and the language remains to be composed

Source: Richards [3]
Image: By User Magnus Manske.
https://commons.wikimedia.org/w/index.php?curid=802079

William Howard **Taft** (US politician 1857–1930):

Don't write so that you can be understood; write so that you can't be misunderstood.

Source: Lebovits [4]
Image: By Harris & Ewing.
https://commons.wikimedia.org/w/index.php?curid=9646114

bioacoustics. Specialists typically work with little interdisciplinary interaction, and the terminology they employ has evolved separately in each discipline, to the point that transdisciplinary misunderstandings are common. Furthermore, societal concern about possible detrimental effects of underwater noise on aquatic animals has led national and international regulators to require monitoring of underwater noise, with a consequent need for interdisciplinary harmonization of terminology [1]. The need for greater clarity in underwater acoustical terminology was recognized in the 1990s and 2000s by Hall [12], [13], Carey [14], [15], and Morfey [16]. These authors each proposed a set of definitions and reporting conventions, but none was adopted widely, with the consequence that multiple books on underwater acoustics each used their own definitions and reporting conventions [17]–[19]. Some progress toward standard terminology was made by ANSI (ANSI S1.1-1994 [20]), the International Electrotechnical Commission (IEC 60050-801:1994 [21]), and the German Institute for Standardization (*Deutsches Institut für Normung*, DIN 1320:2009-12 [22]), all of which included some terms and definitions specific to underwater acoustics, primarily focusing on sonar.

2) History, 2011–2017: International concern for possible adverse effects of underwater noise on aquatic life provided a catalyst for the development of an acoustical lexicon with which to communicate on matters pertaining to underwater acoustics. Of the acoustical terminology standards available in 2011 (see Table I), only four [20]–[23] included terms specific to underwater acoustics, and in all four cases, the underwater

TABLE I
STATUS OF ACOUSTICAL TERMINOLOGY AND RELATED STANDARDS IN 2011

Reference	Title	Notes
ANSI/ASA S1.1-1994 [20]	American National Standard Acoustical Terminology	Some underwater acoustics (sonar only). Superseded by ANSI/ASA S1.1-2013 [24].
ANSI/ASA S3.20-1995 [25]	American National Standard Bioacoustical Terminology	No underwater acoustics. Superseded by ANSI/ASA S3.20-2015 [26].
ANSI/IEEE Std 260.4-1996 [23]	Standard Letter Symbols and Abbreviations for Quantities Used in Acoustics	Some underwater acoustics (sonar only). Superseded by ANSI/IEEE Std 260.4-2018 [27].
DIN 1320:2009-12 [22]	Acoustics – Terminology	Some underwater acoustics (sonar only); in German
IEC 60050-801:1994 [21]	International Electrotechnical Vocabulary - Chapter 801: Acoustics and Electroacoustics	Some underwater acoustics (sonar only).
ISO 80000-3:2006 [28]	Quantities and Units – Part 3: Space and Time	Defines ‘level’ and ‘decibel’. Superseded by ISO 80000-3:2019 [29].
ISO 80000-4:2006 [30]	Quantities and Units – Part 4: Mechanics	Defines pressure. Superseded by ISO 80000-4:2019 [31]
ISO 80000-8:2007 [32]	Quantities and Units – Part 8: Acoustics	No underwater acoustics. Superseded by ISO 80000-8:2020 [33]. The 2020 revision includes some underwater acoustical terminology.
ISO/TR 25417:2007 [34]	Acoustics – Definitions of Basic Quantities and Terms	No underwater acoustics.
ISO 1683:2008 [35]	Acoustics – Preferred Reference Values for Acoustical and Vibratory Levels	No underwater acoustics. Superseded by ISO 1683:2015 [36]. The 2015 revision includes reference values specific to sound in water and other liquids.
ISO 80000-2:2009 [37]	Quantities and Units – Part 2: Mathematical Signs and Symbols to Be Used in the Natural Sciences and Technology	Defines ‘Fourier transform’. Superseded by ISO 80000-2:2019 [38]

acoustical terminology was specific to sonar. In 2011, there existed no standardized terminology for aquatic bioacoustics.

A Dutch-led standardization initiative resulted in the creation of an international ad hoc committee in 2009, with participants from Belgium, Denmark, Germany, Netherlands, Norway, Spain, U.K., and USA, which reported its findings in 2011 [39]. At about the same time, the ASA proposed the creation of an ISO subcommittee on underwater acoustics (see Appendix A), resulting in the creation of ISO/TC 43/SC 3 Underwater Acoustics (SC 3, Chair G. V. Frisk). The subcommittee's inaugural meeting was held in June 2012 at the Woods Hole Oceanographic Institution, where it passed a resolution to create a terminology working group on underwater acoustical terminology (SC 3/WG 2 Terminology, Convenor M. A. Ainslie), henceforth abbreviated “WG2.” In May 2013, WG2 held its inaugural meeting at *Deutsches Institut für Normung* (DIN), Berlin, Germany, and four years later produced ISO 18405 Underwater Acoustics – Terminology, the first international standard terminology dedicated exclusively to underwater acoustics.

C. Standardization of Reference Values

The field quantity most widely used in underwater acoustics is sound pressure, sometimes supplemented by sound particle velocity, equal to the rate of change of the sound particle displacement. The displacement itself can also be of interest [40], [41], as can the sound particle acceleration [42]. The sound particle jerk (rate of change of acceleration) and higher derivatives are rarely considered. In this section, we review standard reference values of sound pressure, sound particle displacement, sound particle velocity, and sound particle acceleration.

Use of the decibel is widespread in acoustics to express levels of quantities. For unambiguous representation of levels, standards for reference values are needed. AStA Z24.1-1942 [8] specified default reference values for two field quantities, namely sound pressure (0.0002 dyn/cm^2, i.e., 20 µPa in SI units), and particle velocity ($5 \cdot 10^{-6}$ cm/s, i.e., 50 nm/s), and for one power quantity, namely sound intensity (10^{-16} W/cm^2, i.e., 1 pW/m^2). None of these reference values saw widespread use for reporting sound levels in water.

1) Sound Pressure and Other Field Quantities: AStA Z24.1-1942 [8] specified 20 µPa and 50 nm/s as reference values of sound pressure and particle velocity without specifying whether the intended medium was a gas or a liquid. AStA Z24.1-1951 [10] introduced a second value of 1 µbar (10^5 µPa), indicating that either 20 µPa or 10^5 µPa may be used in liquids. The modern underwater reference values of sound pressure (1 µPa) and sound particle velocity (1 nm/s) were standardized in 1969 [43] and 1994 [21], respectively (see Table II). In addition to pressure and velocity, modern reference values for displacement (1 pm) and acceleration (1 µm/s^2) were standardized in 2015 [36] (see Table II).

An alternative reference value sometimes used for sound particle velocity, the microvar, was introduced by Siler [47],

TABLE II
NATIONAL AND INTERNATIONAL STANDARD REFERENCE VALUES IN UNDERWATER ACOUSTICS SINCE 1942

Reference	Sound pressure	Sound particle displacement	Sound particle velocity	Sound particle acceleration
AStA Z24.1-1942 [8]*	20 μPa		50 nm/s	
AStA Z24.1-1951 [10]	20 μPa or 10^5 μPa			
ANSI/ASA S1.1-1960 [11]	20 μPa or 10^5 μPa			
ANSI/ASA S1.8-1969 [43]	1 μPa		10 nm/s	10 μm/s^2
ANSI/ASA S1.8-1989 [44]	1 μPa			
IEC 60050-801:1994 [21]	1 μPa		1 nm/s	
ISO 1683:2015 [36]	1 μPa	1 pm	1 nm/s	1 μm/s^2
ANSI/ASA S1.8-2016 [45]	1 μPa	1 pm	1 nm/s	1 μm/s^2
ISO 18405:2017 [46]	1 μPa	1 pm	1 nm/s	1 μm/s^2

Note: Field quantities: One micropascal (1 μPa) is one millionth of a pascal (10^{-6} Pa). One micrometer (1 μm) is one millionth of a meter (10^{-6} m). One nanometer (1 nm) is one billionth of a meter (10^{-9} m). One picometer (1 pm) is one trillionth of a meter (10^{-12} m).
$*$ The 1942 standard does not specify the medium in which sound propagated. We assume it applied to liquid or gas.

who defined it as 1 μbar (10^5 μPa) divided by the characteristic impedance of water (denoted ρc), i.e., approximately 65 nm/s. Siler's proposed reference value was in use at least until 1993 [48]–[51] but was never standardized.

2) Sound Intensity and Other Power Quantities: The reference value for sound intensity in common use has followed an incongruent path that ultimately does not follow the original (and still current) standard value, introduced in 1942. The reference value of sound intensity was specified in AStA Z1.24-1942 [8] as $I_0 = 10^{-16}$ W/cm^2 (1 pW/m^2), and this value has remained in place ever since, becoming recognized for use in underwater acoustics by ANSI in 1969 [43], IEC in 1994 [21], and ISO in 2015 [36].

In 1959, Horton [52] suggested an alternative reference value of sound intensity in water, such that $I_0 = 1$ W/cm^2 (10^{16} pW/m^2), while Urick [53] adopted yet another form, $I_0 = p_0^2/\rho c$, and both forms are incompatible with the 1942 standard. Ultimately, Urick's nonstandard form took hold and has become the modern convention for underwater sound intensity [19], [54]. Applying Urick's convention, in 1967, the implied reference value I_0 of sound intensity in seawater was either approximately $2.6 \cdot 10^{-4}$ pW/m^2 (assuming a reference sound pressure of 20 μPa, as used by Wenz [55]) or $6.5 \cdot 10^3$ pW/m^2 (assuming 10^5 μPa, as used by Urick [53]); unfortunately the precise reference value is rarely if ever stated. In 1969, when 1 μPa was standardized as the modern reference value for sound pressure (see Table II), Urick's convention for the reference sound intensity became $I_0 = 1\ \mu\text{Pa}^2/\rho c \approx 6.5 \cdot 10^{-7}$ pW/m^2. As a justification of this nonstandard reference value for sound intensity, Urick [54] asserted:

"The *unit of intensity* in underwater sound is the intensity of a plane wave having an rms pressure equal to 1 micropascal (abbreviated 1 μPa) or 10^{-5} dyne per square centimeter. This reference intensity has replaced the two previous units in customary use, namely 1 dyn/cm^2 and 0.000204 dyn/cm^2, and is now the American National Standard (ANSI S1.8-1989 [56])".

In our interpretation, Urick's second sentence is intended to be read "This reference intensity has replaced the two previous units in customary use, namely *the intensity of a plane wave of pressure equal to* 1 dyn/cm^2 and 0.000204 dyn/cm^2." In this interpretation, Urick incorrectly claims that the reference intensity of 1 μPa$^2/\rho c$ was the American national standard in 1983, when in fact the American national standard of 1 pW/m^2 was introduced in 1942 and is now the international standard for the reference intensity (see Table III). Thus, 1 μPa$^2/\rho c$ was not and never has been a standard reference value of sound intensity in water. However, 1 μPa$^2/\rho c$ remains in widespread use [19], [57], [58], which leads to uncertainties in interpretation for applications on Earth [1], [59] and beyond [1], [60].

In Urick's interpretation, the value of I_0 depends on the chosen value of ρc, which is usually unspecified, but understood to be approximately 1.5 MPa s/m. Nevertheless, this nonstandard and imprecise reference value of sound intensity is now in widespread use by practitioners of underwater acoustics. On Earth's oceans at atmospheric pressure, the use of $I_0 = 1\ \mu\text{Pa}^2/\rho c$ leads to an ambiguity in sound intensity of a few percent, amounting to values of I_0 between 0.64 and 0.71 aW/m^2 (1 aW = 10^{-6} pW) when considering the representative conditions specified by ANSI [11]. Larger discrepancies arise when one considers fresh water, e.g., for transducer calibration [52], or extreme pressures (up to 10 MPa) or salinities. Urick's convention for I_0 (see [62]) has also been applied to exotic locations such as the hydrocarbon lakes on Titan, one of Saturn's moons [58], where the ambiguity in the associated mean-square sound pressure amounted to a factor of four [1]. To avoid this ambiguity in planetary acoustics, Ainslie and Leighton [60] advocated adherence to the longstanding international standard value (1 pW/m^2) as the reference sound intensity for liquids and gases [21], [36]. We suggest the same advice be applied in Earth's oceans, especially when uncertainty exists in the precise value of ρc (e.g., for detection of objects immersed in sand sediment or bubbly water [1], [59]).

II. STANDARD

A. Overview

The purpose of ISO 18405 [46] is to provide a language for effective communication in underwater acoustics, whether to describe facts or opinions, hypotheses or theories, or any other concepts. Its adoption avoids the need to redefine basic terms

TABLE III
NATIONAL AND INTERNATIONAL STANDARD REFERENCE VALUES IN UNDERWATER ACOUSTICS SINCE 1942

Reference	Sound power	Sound intensity	Sound energy	Sound energy density	Time-integrated squared sound pressure (sound exposure)
AStA Z24.1-1942 [8]*		1 pW/m^2			
AStA Z24.1-1951 [10]					
ANSI/ASA S1.1-1960 [11]		1 pW/m^2			
ANSI/ASA S1.8-1969 [43]	1 pW	1 pW/m^2	1 pJ	1 pJ/m^3	
ANSI/ASA S1.8-1989 [44]	1 pW	1 pW/m^2			
ISO 31-7:1992 [61]	1 pW				
IEC 60050-801:1994 [21]	1 pW	1 pW/m^2			
ISO 1683:2015 [36]	1 pW	1 pW/m^2	1 pJ		1 μPa^2 s
ANSI/ASA S1.8-2016 [45]	1 pW				1 μPa^2 s
ISO 18405:2017 [46]	1 pW		1 pJ		1 μPa^2 s
ISO 80000-8:2020 [33]	1 pW				1 μPa^2 s

Note: Power quantities. One picowatt (1 pW) is one trillionth of a watt (10^{-12} W). One picojoule (1 pJ) is one trillionth of a joule (10^{-12} J).
∗ The 1942 standard does not specify the medium in which sound propagated. We assume that it applied to liquid or gas.

like sound exposure level (SEL), SL, and sound pressure level (SPL) each time these are used. ISO 18405 is based on the International System of Quantities (ISQ), which is described by the fourteen-part standard ISO/IEC 80000, of which *Part 3*: *Space and Time* [28] was the most influential for the development of ISO 18405. ISO 80000-3:2006 [28] defined the term "level of a power quantity" and the unit of level, the decibel. Also relevant are ISO 80000-2:2009 *Mathematical Signs and Symbols to Be Used in the Natural Sciences and Technology* [37], ISO 80000-4:2006 *Mechanics* [30], and ISO 80000-8:2007 *Acoustics* [32].

There are also some things that this standard does not provide.

ISO 18405 is not a measurement standard: ISO 18405 provides conceptual definitions of physical quantities, independent of how these might be measured. For example, it does not specify how SL might be obtained from a measurement of SPL.

ISO 18405 is not a processing standard: ISO 18405 provides conceptual definitions of processed quantities, independent of how the associated processing might be implemented. For example, it specifies neither how to digitize continuous functions for processing on a digital computer nor how to represent an infinite integral as a finite sum.

ISO 18405 is not a reporting standard: ISO 18405 provides conceptual definitions of physical or processed quantities, independent of how their values might be reported. For example, it does not specify how to report levels in decibels.

ISO 18405 is not a repository of regulatory guidelines: ISO 18405 provides conceptual definitions of physical or processed quantities, but it does not provide guidance on acceptable values.

In the following sections, we summarize the contents of ISO 18405, clarifying either the origin or meaning of selected terms.

B. Fundamentals

1) Sound and Sound Pressure: Sound is associated with specific types of fluctuation in pressure or material displacement (particle motion). To qualify as sound, the fluctuations must propagate through the medium and must involve changes in density in the form of local compressions and expansions. For example, a pulsating sphere in water creates sound (in the form of a compressional wave), whereas a surface gravity wave does not create sound (see Table IV), although nonlinear interaction *between* surface gravity waves can create sound [63], [64].

Sound pressure $p(t)$ is the pressure associated with a sound wave. Several different metrics are used to characterize a sound pressure field. Sound pressure varies in time and space, and is usefully characterized by metrics such as peak sound pressure ($p_{\rm pk}$, the maximum value of $|p(t)|$), i.e., using the symbol $\equiv$ to indicate a definition

$$p_{\rm pk} \equiv \max |p(t)| \tag{1}$$

time-integrated squared sound pressure (E, also known as the sound exposure)

$$E \equiv \int_0^T p^2 {\rm d}t \tag{2}$$

and the mean-square sound pressure ($\overline{p^2}$, equal to the ratio of sound exposure to integration time)

$$\overline{p^2} = \frac{E}{T}\ . \tag{3}$$

A quantity closely related to $p_{\rm pk}$ is peak to peak sound pressure, defined as the sum of the peak compressional pressure [$p_{\rm pk,c} = \max p(t)$] and the peak rarefactional pressure [$p_{\rm pk,r} = \max(-p(t))$] within a specified time interval

$$p_{\rm pk,pk} \equiv p_{\rm pk,c} + p_{\rm pk,r}. \tag{4}$$

2) Sound Pressure Spectrum and Plancherel's Theorem: The sound pressure spectrum is related to sound exposure via Plancherel's theorem (a continuous version of Parseval's theorem, stating the integral over all time of the square of a real function is equal to the integral over all frequency of the squared modulus of its Fourier transform). Sound exposure can also be written as an integral over the energy spectral density. Extending the integral to positive and negative infinity for a transient contained within the time interval [0, T] and making use of Plancherel's theorem, it follows that

$$\int_{-\infty}^{+\infty} p(t)^2 {\rm d}t\ = \int_{-\infty}^{+\infty} |P(f)|^2\, {\rm d}f \tag{5}$$

TABLE IV
EXAMPLES OF ACOUSTIC (BLUE SHADING) AND NONACOUSTIC PRESSURE (UNSHADED) FLUCTUATIONS

Is it sound?	fluctuations involve local changes in density	fluctuations do not involve local changes in density
fluctuations propagate	**Yes**. Acoustic fluctuations include compressional waves, shear waves and interface waves.	**No**. Propagating non-acoustic fluctuations include surface gravity waves.
fluctuations do not propagate	**No**.	**No**. Non-acoustic fluctuations that neither propagate nor involve a change density include fluctuating hydrodynamic flow.

where the sound pressure spectrum $P(f)$ is the Fourier transform of $p(t)$

$$P(f) \equiv \int_{-\infty}^{+\infty} p(t) \exp(-2\pi i f t)\, dt. \tag{6}$$

3) Power and Root-Power Quantities: Quantities proportional to the square of sound pressure (e.g., E, $\overline{p^2}$) are also proportional to sound power and are therefore referred to as "power quantities" because all are proportional to $\overline{p^2}$ for some value of the averaging time T. The square root of these ($E^{1/2}$, p_{rms}) are considered root-power quantities because they are proportional to $p_{\mathrm{rms}} = (\overline{p^2})^{1/2}$.

4) Level and the Decibel: Metrics computed from the sound pressure are often expressed as a level in decibels, such as SPL. In general, a level of a quantity Q is the logarithm of a ratio of Q to a specified reference value, Q_0, of that quantity [65]

$$L_Q \equiv \log_\beta \frac{Q}{Q_0}\ [L_Q]. \tag{7}$$

A complete specification of the level requires the unit $[L_Q]$ and reference value Q_0 to be specified. The base β is also needed, and usually follows once the unit is stated. When a power quantity Q_P is expressed as a level in decibels, this equation becomes (see Appendix B)

$$L_P = 10\log_{10} \frac{Q_P}{Q_{P,0}}\ \mathrm{dB}. \tag{8}$$

Equation (8) has the same form as (7) and can be derived from it with the substitutions $[L_Q] = \mathrm{dB}$ and

$$\beta = 10^{1/10}. \tag{9}$$

We refer to (8) as the "10 log" rule for the level of a power quantity. The same equation can be written as

$$L_P = 20\log_{10} \frac{{Q_P}^{1/2}}{Q_{P,0}^{1/2}}\ \mathrm{dB} \tag{10}$$

which we refer to as the "20 log" rule for the level of a root-power quantity. The level of the power quantity Q_P with reference value $Q_{P,0}$ is identical to the level of the root-power quantity ${Q_P}^{1/2}$ if its reference value is $Q_{P,0}^{1/2}$.

5) Reference Values: Where possible, ISO 18405:2017 [46] follows existing standards for reference values, primarily following ISO 1683:2015 [36]. Where needed, new values were introduced, such as 1 μPa^2 m^2 for the source factor, following Morfey [16], and 1 (nm/s)^2 s for time-integrated squared sound particle velocity, following Bolle *et al.* [66]. In addition, 1 pm^2 s and 1 (μm/s^2)^2 s were introduced for the time-integrated squared particle displacement and acceleration, as well as 1 μPa^2 m^2 s for the energy source factor.

6) Time-Integrated Squared Sound Pressure Level (Sound Exposure Level, SEL): SEL, also known as the time-integrated squared sound pressure level, is defined by ISO 18405:2017 [46] as the level (with reference to ${p_0}^2 t_0$) of the *unweighted* sound exposure

$$L_E \equiv 10\log_{10} \frac{E}{{p_0}^2 t_0}\ \mathrm{dB} \tag{11}$$

reflecting the way this term is used in underwater acoustics [67]–[70]. This use contrasts with convention in airborne acoustics, for which the same term can imply a frequency weighted quantity [24], [34]. According to ISO 18405:2017 [46], the level of the *weighted* sound exposure is the "weighted sound exposure level" [see (62)], thereby distinguishing between weighted and unweighted sound exposure terms. The reference values p_0 and t_0 are 1 μPa and 1 s, respectively.

7) Mean-Square Sound Pressure Level and Peak Sound Pressure Level: Mean-square sound pressure level is the level (with reference to ${p_0}^2$) of the mean-square sound pressure, $\overline{p^2}$, i.e., [46]

$$L_p \equiv 10\log_{10} \frac{\overline{p^2}}{{p_0}^2}\ \mathrm{dB}. \tag{12}$$

A synonym of *mean-square sound pressure level* is *root-mean-square sound pressure level*. Either term may be abbreviated *sound pressure level* or *SPL*. The symbol is L_p or $L_{p,\mathrm{rms}}$.

Zero-to-peak sound pressure level is the level (with reference to p_0) of the peak sound pressure, $p_{\mathrm{pk}} = \max |p(t)|$, i.e.,

$$L_{p,0-\mathrm{pk}} \equiv 10\log_{10} \frac{p_{\mathrm{pk}}^2}{{p_0}^2}\ \mathrm{dB}. \tag{13}$$

The reference sound pressure, i.e., p_0, is squared for consistency with the 10 log rule.

A synonym of *zero-to-peak sound pressure level* is *peak sound pressure level*. This quantity differs from "peak sound level" as defined by ANSI S1.1-2013 [24] and "peak sound pressure level" as defined by ISO/TR 25417:2007 [34], both of which are weighted quantities. No frequency or time weighting is involved in L_p (SPL or Lrms) or $L_{p,0-\mathrm{pk}}$ (Lpk).

The reference value for Lrms or Lpk may be stated either as ${p_0}^2$ (1 μPa^2) (10 log rule) or as p_0 (1 μPa) (20 log rule). Lrms and Lpk depend on one's choice of analysis time window and

TABLE V
UNITS OF LFR: OCTAVE AND INTEGER SUBMULTIPLES (BASED ON [81])

Unit name	Exact value in octaves (oct)	Value to five significant figures in millidecades (mdec)	Notes
Octave **symbol**: oct	1	301.03	1 oct = $\log_{10}2$ dec source: ISO 80000-8:2020 [33]
One-third octave	1/3	100.34	source: ISO 18405:2017 [46] also known as: one-third octave (base 2)
One-sixth octave	1/6	50.171	In musical acoustics, an alternative name for this term is *equal temperament tone* [81] also known as: one-sixth octave (base 2)
Decioctave **symbol**: doct	1/10	30.103	
One-twelfth octave	1/12	25.086	In musical acoustics, an alternative name for this term is *equal temperament semitone* [24, 81] also known as: one-twelfth octave (base 2)
Centioctave **symbol**: coct	1/100	3.010 3	
Millioctave **symbol**: moct	1/1000	0.301 03	source: Pikler [81]
Cent	1/1200	0.250 86	source: Pikler [81]

frequency band. Compliance with ISO 18405:2017 [46] requires averaging time and frequency band to be stated.

The widely used [71]–[77] abbreviation "peak SPL" is misleading (and is deprecated by ISO 18405:2017 [46]) because, if taken literally, it would mean the maximum value of SPL, i.e.,

$$L = \max\left(10\log_{10}\frac{\overline{p^2}}{p_0^2}\text{ dB}\right) \tag{14}$$

when what is intended is (13). We suggest instead the alternative abbreviation "Lpk" (*l*evel of the *peak* sound pressure).

Although not explicitly deprecated, the abbreviation "rms SPL" is similarly misleading because, if taken literally, it would mean the rms value of SPL, i.e.,

$$L = \sqrt{\overline{(L_p)^2}} \tag{15}$$

when what is intended is (12). We suggest instead the alternative abbreviation "SPL" or "Lrms" (*l*evel of the *rms* sound pressure).

The term "peak-to-peak sound pressure level" is sometimes encountered. This term is not defined by ISO 18405:2017 [46] because $p_{\mathrm{pk-pk}}$ is not a root-power quantity.

8) Spectral Density Levels: Either sound exposure (E) or mean-square sound pressure ($\overline{p^2}$) can be expressed as a spectral density level. For example, if ΔE and $\Delta\overline{p^2}$ are the sound exposure and mean-square sound pressure in a specified frequency band (bandwidth Δf), the energy spectral density level (with reference to $p_0^2 t_0/f_0$) and power spectral density level (with reference to p_0^2/f_0) are, respectively

$$L_{E,f} = 10\log_{10}\frac{\Delta E/\Delta f}{p_0^2 t_0/f_0}\text{ dB} \tag{16}$$

and

$$L_{p,f} = 10\log_{10}\frac{\Delta\overline{p^2}/\Delta f}{p_0^2/f_0}\text{ dB} \tag{17}$$

where the reference value f_0 is 1 Hz.

9) Multiplication and Division Rules for Reference Values: If two logarithmic quantities, in decibels, are combined by addition, their reference values can be combined by multiplication. In equation form, if

$$\Lambda_A = 10\log_{10}\frac{A}{A_0}\text{ dB} \tag{18}$$

and

$$\Lambda_B = 10\log_{10}\frac{B}{B_0}\text{ dB} \tag{19}$$

it follows that

$$\begin{aligned}\Lambda_A + \Lambda_B &= 10\log_{10}\frac{A}{A_0}\text{ dB} + 10\log_{10}\frac{B}{B_0}\text{ dB}\\ &= 10\log_{10}\frac{AB}{A_0B_0}\text{ dB}.\end{aligned} \tag{20}$$

In other words, the reference value for the sum $\Lambda_A + \Lambda_B$ is the product of the reference values for Λ_A and Λ_B individually, A_0B_0. For example, the SEL can be written as

$$\begin{aligned}L_E &= 10\log_{10}\frac{E}{E_0}\text{dB} = 10\log_{10}\frac{\overline{p^2}}{p_0^2}\text{ dB} + 10\log_{10}\frac{T}{t_0}\text{ dB}\\ &= 10\log_{10}\frac{\overline{p^2}T}{p_0^2 t_0}\text{ dB}.\end{aligned} \tag{21}$$

Given that $E = \overline{p^2}\,T$, we conclude that $E_0 = p_0^2\,t_0$, consistent with the multiplication rule.

Similarly, if two logarithmic quantities, in decibels, are combined by subtraction, their reference values are combined by division. In equation form

$$\begin{aligned}\Lambda_A - \Lambda_B &= 10\log_{10}\frac{A}{A_0}\text{ dB} - 10\log_{10}\frac{B}{B_0}\text{ dB}\\ &= 10\log_{10}\frac{A/B}{A_0/B_0}\text{ dB}.\end{aligned} \tag{22}$$

In other words, the reference value for the difference $\Lambda_A - \Lambda_B$ is the ratio of the reference values for Λ_A and Λ_B separately,

A_0/B_0. For example, the mean-square sound pressure spectral density level can be written

$$L_{p,f} = 10\log_{10}\frac{\left(\overline{p^2}\right)_f}{\left(\overline{p^2}\right)_{f,0}}\ \mathrm{dB} = 10\log_{10}\frac{\Delta\overline{p^2}}{p_0^2}\ \mathrm{dB} - 10\log_{10}\frac{\Delta f}{f_0}\ \mathrm{dB}$$

$$= 10\log_{10}\frac{\Delta\overline{p^2}/\Delta f}{p_0^2/f_0}\ \mathrm{dB}. \quad (23)$$

Given that $(\overline{p^2})_f = \Delta\overline{p^2}/\Delta f$, we conclude that $(\overline{p^2})_{f,0} = p_0^2/f_0$, consistent with the division rule.

The multiplication and division rules for reference values work if one adheres consistently to either the 10 log or 20 log rule for levels. They do not work if the 10 log and 20 log rules are mixed.

For the rest of this article, we follow the 10 log rule. For example, for SPL and SDL, we use 1 $\mu\mathrm{Pa}^2$ and 1 $\mu\mathrm{Pa}^2$/Hz as the reference values. (Application of the 20 log rule would lead to the square root of these reference values, i.e., 1 μPa and 1 μPa/$\mathrm{Hz}^{1/2}$, which are also compliant with ISO 18405:2017 [46].)

10) Data Processing (Standard Frequency Bands): An important step in acoustical data processing is the choice of frequency band. Octave bands and decade bands are common. The octave and decade are units of logarithmic frequency ratio (LFR), corresponding respectively to a factor 2 and 10 increase or decrease in frequency [33]. Thus, 60 Hz is one octave lower than 120 Hz, and 50 Hz is one decade lower than 500 Hz.

a) Octave and fractional octave bands: The definition of "octave" as a unit of LFR corresponding to a factor two in frequency was introduced in the 18th century [78], [79] and standardized in the 1940s [8]. By definition, an LFR (or "frequency level" [24], [65], [79], [80]) may be expressed in the form $\log_\beta(f_2/f_1)$ [81]. The octave is the unit of LFR when the base β of the logarithm is 2 [65]. In an equation form, the LFR between f_1 and f_2 is [33]

$$G = \log_2\frac{f_2}{f_1}\ \text{oct}. \quad (24)$$

Smaller units based on the octave are obtained by dividing the octave by an integer (see Table V).

b) Decade and fractional decade bands: The decade (dec) is a unit of LFR corresponding to a factor 10 in frequency. In other words, it is the unit of LFR when the base of the logarithm is 10. In equation form [33]

$$G = \log_{10}\frac{f_2}{f_1}\ \text{dec}. \quad (25)$$

Smaller units based on the decade are obtained by dividing the decade by an integer (see Table VI).

c) Standard one-tenth decade (decidecade) bands: Modern standards for acoustical data analysis use base 10 frequency bands [82], [85], of which one of the most widely used is 1/10 dec (1 ddec). Because 1/10 dec is approximately equal to 1/3 oct (Box 2), the term "one-third octave" is sometimes used loosely to mean 1/10 dec [85], [86], making it difficult to discern whether 1/3 oct or 1/10 dec is intended. ANSI/ASA S1.6-2016 [82] made a step toward clarifying the distinction by introducing the term "one-tenth-decade" to mean 1/10 dec, but ultimately prolonged the confusion by using the term "1/3 octave" to mean 1/10 dec (see Table 2 of [82]). To address this problem, ISO 18405:2017 [46] facilitates disambiguation by introducing the term "decidecade" to mean 1/10 dec, reserving "one-third octave" to mean 1/3 oct (see Table VII). The present authors recommend the use of unambiguous terms like "decidecade" for the base 10 unit and "one-third octave (base 2)" for the base 2 unit [46].

BOX 2

The difference between one-third of an octave and one-tenth of a decade is small, and for some applications may be neglected. The near coincidence between ten octaves and three decades ($2^{10} \approx 10^3$) is identical to the one that causes confusion in the computer industry by use of the term "kilobyte" to mean 1024 B [87] when the internationally accepted use of the prefix kilo requires it to mean 1000 B [88]. To facilitate a clear distinction between the two meanings, in 1998, the IEC introduced the new term "kibibyte" to mean 1024 B (IEC, 1998) [89], thus distinguishing it from kilobyte (= 1000 B), and the prefix kibi is one of a number of prefixes now defined in the ISQ to distinguish unambiguously between powers of 2 and powers of 10 [90], [91].

In acoustics, while one kilohertz (1 kHz) is 1000 Hz, one kibihertz (1 KiHz) is 1024 Hz, 10 octaves above 1 Hz [92], [93]. If the interval between 1 Hz and 1 kHz is divided into 30 equal subintervals, the size of each subinterval is equal to one-tenth of a decade but is sometimes referred to for historical reasons as a "one-third octave."

C. Source Properties

Terms used to characterize the acoustical output of underwater sound sources include source waveform, source factor, and SL. ISO 18405:2017 [46] gives these terms precise meaning.

1) Source Waveform and Source Spectrum: Source waveform $s(t)$ is the basic building block from which many other source properties are derived. Its formal definition reads "product of distance in a specified direction, r, from the *acoustic center* of a sound source and the delayed *far-field sound pressure*, $p(t - t_0 + r/c)$, for a specified time origin, t_0, if placed in a hypothetical infinite uniform lossless medium of the same density and sound speed, c, as the actual medium at the location of the source, with identical motion of all acoustically active surfaces as the actual source in the actual medium," In a lossless and boundary-free medium, this definition simplifies to the product of the sound pressure p and distance r in a specified direction and in the source's far field.

The source spectrum $S(f)$ is defined as the Fourier transform of the source waveform

$$S(f) \equiv \int_{-\infty}^{+\infty} s(t)\exp(-2\pi \mathrm{i} f t)\,\mathrm{d}t. \quad (26)$$

2) Source Factor and Energy Source Factor: For a transient source, limited in time to the interval 0 to T, the energy source

TABLE VI
UNITS OF LFR: DECADE AND INTEGER SUBMULTIPLES

Unit name	**Value to five significant figures in millioctaves (moct)**	**Exact value in millidecades (mdec)**	**Notes**
Decade **symbol**: dec	3,321.9	1000	1 dec = $\log_2 10$ oct source: ISO 80000-8:2020 [33]
Decidecade **symbol**: ddec	332.19	100	Alternative names for this term are "one-tenth decade" ANSI/ASA S1.6-2016 [82] and "one-third octave (base 10)" 18405:2017 [46]
Centidecade **symbol**: cdec	33.219	10	
Millidecade **symbol**: mdec	3.3219	1	An alternative name for this term is "savart" [81]. See also [83];[84]

TABLE VII
HISTORY OF STANDARD TERMINOLOGIES FOR 1/10 DEC AND 1/3 OCT FREQUENCY BANDS

Ref.	**Title**	**Name for one-tenth of a decade (1/10 dec)**	**Name for one-third of an octave (1/3 oct)**
ISO 266:1997 [86]	Acoustics–Preferred Frequencies	"one-third-octave"	N/A
ANSI S1.11-2004 [94]	Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters	"one-third-octave"	"one-third-octave"
IEC 61260-1:2014 [85]	Electroacoustics –Octave-Band and Fractional-Octave-Band Filters –Part 1: Specifications *note:* adopted nationally by ANSI as ANSI/ASA S1.11-2014/Part 1	"one-third-octave"	N/A
ANSI S1.6-2016 [82]	American National Standard: Preferred Frequencies and Filter Band Center Frequencies for Acoustical Measurements	"one-tenth-decade" or "1/3 octave"	"one-third-octave"
ISO 18405:2017 [46]	Underwater Acoustics –Terminology	"decidecade" or "one-third-octave (base 10)"	"one-third-octave" or "one-third-octave (base 2)"

factor ($F_{\mathrm{S},E}$), or sound exposure source factor, is the time-integrated squared source waveform

$$F_{\mathrm{S},E} \equiv \int_0^T s(t)^2 \mathrm{d}t. \tag{27}$$

The source factor is the mean-square value of the source waveform, i.e.,

$$F_{\mathrm{S}} \equiv \frac{F_{\mathrm{S},E}}{T}. \tag{28}$$

3) Source Level (SL) and Energy Source Level (ESL): SL is a property of any underwater sound source with an acoustic far field [18] (sources that extend through the entire water column and are in rigid contact with the seabed do not have a far field [95]). On its own, the SL provides no information about the acoustic near field. SL (L_{S}) is defined as [46]

$$L_{\mathrm{S}} \equiv 10\log_{10}\frac{F_{\mathrm{S}}}{1\,\mu\mathrm{Pa}^2\mathrm{m}^2}\mathrm{dB}. \tag{29}$$

If PL (symbol N_{PL}) is known, then SL can be obtained from SPL and PL [see (36)] via [46]

$$L_{\mathrm{S}} = L_p\ (r) + N_{\mathrm{PL}}\,(r)\,. \tag{30}$$

ESL (symbol $L_{\mathrm{S},E}$), or sound exposure source level, is a property of any transient underwater sound source with a far field. It is related to the radiated sound energy in that far field, and is defined as [46]

$$L_{\mathrm{S},E} \equiv 10\log_{10}\frac{F_{\mathrm{S},E}}{1\,\mu\mathrm{Pa}^2\mathrm{m}^2\mathrm{s}}\ \mathrm{dB}. \tag{31}$$

ESL is related to SEL and sound exposure propagation loss (EPL, symbol $N_{\mathrm{PL,E}}$) via [46]

$$L_{\mathrm{S},E} = L_E\ (r) + N_{\mathrm{PL},E}\,(r)\,. \tag{32}$$

For a source in an infinite medium (far from reflecting boundaries) of characteristic impedance ρc, the SL is related to the far-field radiant intensity (power per unit solid angle, W_Ω) [18]

$$L_{\mathrm{S}} = \ 10\log_{10}\frac{\rho c W_\Omega}{1\,\mu\mathrm{Pa}^2\mathrm{m}^2}\,\mathrm{dB} \tag{33}$$

and the ESL is related in a similar way to the energy per unit solid angle (E_Ω)

$$L_{\mathrm{S},E} = \ 10\log_{10}\frac{\rho c E_\Omega}{1\,\mu\mathrm{Pa}^2\mathrm{m}^2\mathrm{s}}\ \mathrm{dB}. \tag{34}$$

The reference value $1\,\mu\mathrm{Pa}^2\mathrm{m}^2$ (or $1\,\mu\mathrm{Pa}^2\mathrm{m}^2\mathrm{s}$) is sometimes written inappropriately as "1 µPa @ 1 m" (or "1 µPa^2 s @ 1 m").

The present authors discourage this practice because it gives the incorrect impression that SL is the SPL at a distance of 1 m from the source (or that ESL is the SEL at 1 m), when in fact SL is a far-field property of the source, rarely (if ever) equal to the SPL at 1 m from the source. It can be obtained using (30) by adding the SPL at any position in the source's far-field measurement to the PL from the source to the same far-field position. Its reference value can be obtained from the multiplication rule (see Section II-B1).

4) Source Properties Discussion: The concepts of SL and ESL are properties of any underwater sound source with a far field. SL is used typically for continuous sounds (sonar transmitters, transponders, fish or mammal communication signals, wind, and precipitation), whereas ESL is more appropriate for time-limited sources producing transient sounds (airguns, mammal echolocation clicks, and shrimp snaps). However, real sources are diverse in nature [96], and the basic concepts introduced above in some applications need to be adapted to take into account the following properties:

1) the energy or power radiated per unit frequency band [83], [97];
2) for near-surface sources, the energy or power radiated by a combination of the source and its surface reflected image [83], [98];
3) the energy or power radiated per unit surface area [83], [98];
4) statistics of the source waveform other than its mean-square value such as zero to peak [99].

Definitions of levels associated with these concepts are not provided by ISO 18405:2017 [46]. The onus is therefore on individual authors to define terms as needed, which is the first step in the standardization process. The more widely accepted a concept becomes and the greater its utility, the likelier it is to be included in a future terminology standard.

D. Propagation and Scattering

1) Transmission Loss (TL) and Propagation Loss (PL): Two widely used terms in underwater acoustics are "TL" and "PL." They are sometimes used interchangeably but ISO 18405 appropriately distinguishes between them.

a) Transmission loss (TL): TL is defined [16], [46] as the difference between two values of levels at different locations $(\boldsymbol{x}_1,\ \boldsymbol{x}_2)$

$$\Delta L_{\mathrm{TL}} \equiv L\left(\boldsymbol{x}_1\right) - L\left(\boldsymbol{x}_2\right). \tag{35}$$

For example, one might place a hydrophone either side of an acoustic barrier and characterize the effectiveness of the barrier in terms of the TL between the two hydrophones. TL has no reference value because $L(\boldsymbol{x}_1)$ and $L(\boldsymbol{x}_2)$ are levels of like quantities—their reference values cancel. It is understood that $\boldsymbol{x}_1$ is closer to a specified sound source or group of sources than $\boldsymbol{x}_2$ such that TL is conventionally a positive number. The above-mentioned definition can be traced to AStA Z24.1-1951 [10], which defined TL as a "general term used to denote a decrease in power in transmission from one point to another."

b) Propagation loss (PL): Following Horton [52], Morfey [16], and Ainslie [100], ISO 18405 [46] defines PL as the difference between the SL and the received SPL at a specified location ($\boldsymbol{x}$)—see, e.g., [101]–[103]

$$N_{\mathrm{PL}}\left(\boldsymbol{x}\right) \equiv L_{\mathrm{S}} - L_p\left(\boldsymbol{x}\right). \tag{36}$$

The concept of PL was introduced above (30) as the difference between SL and SPL. Thus, if SL is known, PL provides a simple way of calculating SPL as

$$L_p = L_{\mathrm{S}} - N_{\mathrm{PL}}. \tag{37}$$

c) Propagation loss (PL) versus transmission loss (TL): The quantity N_{PL} defined by (36) is widely referred to as "TL" [19], [54], but this use leads to a clash with (35). ISO 18405:2017 [46] distinguishes between TL and PL, giving ΔL_{TL} (TL) and N_{PL} (PL) separate identities according to (35) and (36).

Two conceptual differences between ΔL_{TL} and $N_{\mathrm{PL}}(\boldsymbol{x})$, as defined by (35) and (36), respectively, are that $N_{\mathrm{PL}}(\boldsymbol{x})$ is a function of only one spatial variable (not two), and, unlike ΔL_{TL}, is the difference between two unlike quantities, for which the reference values do not cancel. A third important difference between PL and TL concepts, implied by the defining equations but not immediately apparent, is that because PL is defined in terms of SL, whose existence requires a far field, the existence of PL also requires the existence of a far field.

The reference value for $N_{\mathrm{PL}}(\boldsymbol{x})$ can be deduced from (36) (with the division rule) as the ratio of 1 μPa^2 m^2 (reference value for L_{S}) to 1 μPa^2 (that for L_p), namely 1 m^2.

2) Scattering: The quantities "differential scattering cross section," "backscattering cross section," and "TS" are closely related and widely used. Differential scattering cross section and TS are used in a consistent way and are defined unambiguously by ISO 18405, whereas backscattering cross section received detailed consideration as it is used differently in different branches of acoustics.

a) Differential scattering cross section: The differential scattering cross section σ_Ω is a property of an object of finite extent ensonified by an infinite plane wave. In general, the power scattered by the object varies with angle and can be quantified by its radiant intensity (power per unit solid angle) W_Ω in a specified direction (i.e., $W_\Omega = I_{\mathrm{out}}\, r^2$, where I_{out} is the far-field intensity in the specified direction at distance r). The differential scattering cross section is defined as the ratio of the radiant intensity of the scattered field in that direction to the intensity I_{in} of the incident plane wave

$$\sigma_\Omega \equiv \frac{W_\Omega}{I_{\mathrm{in}}} = \frac{I_{\mathrm{out}} r^2}{I_{\mathrm{in}}}. \tag{38}$$

b) Backscattering cross section in acoustics: In acoustics, the backscattering cross section σ_{bs} has two different definitions that we distinguish using superscripts (1) and (2). It was defined by ANSI S1.1-1960 [11] as

$$\sigma_{\mathrm{bs}}^{(1)} \equiv 4\pi\sigma_{\Omega,\mathrm{bs}} \tag{39}$$

which remains the modern national standard in the USA [24] and Germany [22]. This standard definition is followed by multiple authors [16], [18], [53], [54], [104], [105].

In 1977, an alternative definition was introduced [106]

$$\sigma_{\mathrm{bs}}^{(2)} \equiv \sigma_{\Omega,\mathrm{bs}} \tag{40}$$

and widely adopted in fisheries acoustics [107]–[111], creating a conflict with the longstanding ANSI definition. In 2016, WG2 was unable to agree on which of the parallel definitions to adopt, with the consequence that ISO 18405:2017 [46] does not define this term, leaving an ambiguity in underwater acoustical terminology. As an example to illustrate the difference, consider a rigid sphere of radius α, for which in the high frequency limit $\sigma_{\mathrm{bs}}^{(1)} = \pi\alpha^2$, whereas $\sigma_{\mathrm{bs}}^{(2)}$ is 4 π times smaller.

c) Backscattering cross section in electromagnetism: The concept of backscattering cross section is used in radar physics [112] and in optics [113]. In both disciplines, the backscattering cross section is defined as the ratio of power scattered by an equivalent sphere (one that scatters the same radiant intensity W_Ω in all directions as the real object does in the backscattering direction, i.e., $W_\Omega = I_{\mathrm{bs}}\, r^2$, where I_{bs} is the intensity in the backscattering direction at distance r) to the incident intensity

$$\sigma_{\mathrm{bs}} = 4\pi \left(\frac{r^2 I_{\mathrm{bs}}}{I_{\mathrm{in}}}\right). \tag{41}$$

Noting that the term in parentheses is the differential scattering cross section in the backscattering direction, it follows that the radar and optics definition corresponds to that of (39).

d) Scattering discussion and recommendation: The concept of backscattering cross section is a useful one, and its value in underwater acoustics can be enhanced by adopting a single definition. The ambiguity can be resolved in the short term by defining the quantity each time it is used or sidestepped by avoiding its use altogether, and instead using the differential scattering cross section σ_Ω or target strength N_{TS}. Specifically, N_{TS} is defined in terms of σ_Ω [46]

$$N_{\mathrm{TS}} \equiv 10\log_{10}\frac{\sigma_\Omega}{1\ \mathrm{m}^2\ \mathrm{sr}^{-1}}\mathrm{dB}. \tag{42}$$

In the longer term, it is desirable to harmonize on a single standard definition of backscattering cross section. The present authors advocate adopting the definition that is used in other branches of physics, i.e., (39).

E. Signal Duration and Bandwidth

Important properties of acoustic signals are their duration and bandwidth. For example, in sonar analysis the effective signal bandwidth and effective signal duration of an active sonar pulse are closely related to the range and velocity resolution of the sonar [114]. The concept of signal duration is also used in underwater noise management, for example, to determine the averaging time used for estimation of the rms sound pressure associated with impulsive sound [67]. ISO 18405:2017 [46] defines three different kinds of signal duration (see clause 3.5), namely the threshold exceedance signal duration (e.g., the duration between 10-dB points), the percentage energy signal duration (typically between 5% and 95% cumulative energy points), and the effective signal duration (defined in terms of the envelope of the analytic signal, a complex representation of the sound pressure time series).

F. Sonar Equations

Early work in underwater acoustics (see [115], [116], and [18, Ch. 1]) was dedicated primarily to the development and use of sonar. The sonar equation is a tool for quantifying the performance of sonar systems. In its most general form, the sonar equation relates the signal to noise ratio R_{SN} to the detection threshold (DT) ΔL_{DT} and signal excess ΔL_{SE} as

$$\Delta L_{\mathrm{SE}} = 10\log_{10}\frac{R_{\mathrm{sn}}}{R_{\mathrm{sn},50}}\mathrm{dB} \tag{43}$$

where

$$R_{\mathrm{sn},50} = 10^{\Delta L_{\mathrm{DT}}/(10\ \mathrm{dB})}. \tag{44}$$

The DT is the value of $10\log_{10}R_{\mathrm{sn}}$ dB for a specified detection probability (in this case 50%). The signal excess is the amount by which this threshold is exceeded.

Different sonar equations are used for active and passive sonar although both are based on (43). The passive sonar equation is simpler and is described first (see Section II-F1). No approximation is necessary in the derivation of the passive sonar equation although its precise form depends on whether one is considering ratios of mean-square sound pressure (MSP) or ratios of equivalent plane wave intensity (EPWI) (see Section II-F2).

Unlike the passive sonar equation, the usual form of the active sonar equation (see Section II-F3) involves an approximation resulting from the assumption of an incoming plane wave in the definition of the TS term. This approximation is removed by replacing TS with equivalent target strength (eqTS) (see Section II-F4)

1) Passive Sonar Equation: The passive sonar equation is usually written in logarithmic form by expressing the signal-to-noise ratio (ratio of signal power to noise power R_{sn}) after specified processing as a level difference (difference between signal level and noise level) in decibels.

The SPL of the signal at the sonar receiver is

$$L_{p,\mathrm{s}} = L_{\mathrm{S}} - N_{\mathrm{PL}}. \tag{45}$$

If $L_{p,\mathrm{n}}$ is the SPL of the noise at the sonar receiver and ΔL_{PG} is the processing gain after the specified processing, then

$$\begin{aligned} 10\log_{10}R_{\mathrm{sn}}\mathrm{dB} &= L_{p,\mathrm{s}} - L_{p,\mathrm{n}} + \Delta L_{\mathrm{PG}} \\ &= L_{\mathrm{S}} - N_{\mathrm{PL}} - L_{p,\mathrm{n}} + \Delta L_{\mathrm{PG}}. \end{aligned} \tag{46}$$

Equation (46) follows directly from the definitions of the individual terms and the assumption of negligible nonacoustic noise.

2) Mean-Square Pressure or Equivalent Intensity?: The individual sonar equation terms are logarithms of ratios of power-like quantities, but which power-like quantity should be used? When Horton introduced his passive and active listening equations in 1959, he chose EPWI, namely the sound intensity of an equivalent plane wave of the same rms sound pressure.

Urick [53] also used EPWI ratios to define individual terms, but with a different reference value, $I_0 = p_0^2/\rho c$ (with ρc a nominal value of impedance of seawater), initially specified as 0.64 aW/m^2 (Urick in 1967 [53]) and later (in 1975 [95] and 1983 [53]) as 0.67 aW/m^2. ISO 18405:2017 [46] follows this modern (MSP) use, omitting impedance ratios. Following the MSP choice ensures that mainstream acoustic propagation models [19], [117], which overwhelmingly follow the MSP convention [59], [62], produce ISO 18405-compatible output without the need to correct for the impedance ratio between source and receiver.

3) Active Sonar Equation: The active sonar equation can be written in the approximate form as

$$10\log_{10}R_{\mathrm{sn}}\mathrm{dB} \approx L_{\mathrm{S}} - N_{\mathrm{PL,Tx}} + N_{\mathrm{TS}} - N_{\mathrm{PL,Rx}} - L_{p,\mathrm{n}} + \Delta L_{\mathrm{PG}} \quad (47)$$

where subscripts are used to indicate propagation from the sonar transmitter "Tx" (or to the receiver "Rx"). As with passive sonar, the individual terms are logarithms of ratios of mean-square sound pressure (not EPWI). The definition of TS requires an incoming plane wave and a scattered spherical wave. If these conditions are met, (47) provides a useful approximation to reality.

4) Target Strength (TS) and Equivalent Target Strength (eqTS): TS (symbol N_{TS}) is defined by means of (42). It is a bistatic quantity in the sense that it can be evaluated for any incident angle and any scattered angle. By comparison, the eqTS (symbol $N_{\mathrm{TS,eq}}$) is defined by rearranging the terms of the active sonar equation

$$N_{\mathrm{TS,eq}} \equiv L_{p,\mathrm{TE}} + N_{\mathrm{PL,Tx}} + N_{\mathrm{PL,Rx}} - L_{\mathrm{S}} \quad (48)$$

where the terms on the right-hand side are the echo level (L_{TE}), the outward and return PL ($N_{\mathrm{PL,Tx}}$ and $N_{\mathrm{PL,Rx}}$), and the SL (L_{S}).

If the conditions described above for the use of (47) are not met, the TS term needs to be replaced by eqTS [18], [46], resulting in the exact expression as

$$10\log_{10}R_{\mathrm{sn}}\mathrm{dB} = L_{\mathrm{S}} - N_{\mathrm{PL,Tx}} + N_{\mathrm{TS,eq}} - N_{\mathrm{PL,Rx}} - L_{p,\mathrm{n}} + \Delta L_{\mathrm{PG}}. \quad (49)$$

A further approximation is sometimes made [19], [54] for monostatic sonar by assuming the two PL terms equal

$$10\log_{10}R_{\mathrm{sn}}\mathrm{dB} \approx L_{\mathrm{S}} - 2N_{\mathrm{PL}} + N_{\mathrm{TS,eq}} - L_{p,\mathrm{n}} + \Delta L_{\mathrm{PG}}. \quad (50)$$

This approximation is appropriate if the sonar and target are in seawater (if the medium density is the same for both). If either sonar or target is not in seawater (e.g., if in a bubbly layer, or buried in the sediment), the approximation $N_{\mathrm{PL,Tx}} \approx N_{\mathrm{PL,Rx}}$ no longer holds and a correction is necessary [59]. For planetary acoustics, large spatial variations in medium density can invalidate the assumption that $N_{\mathrm{PL,Tx}}$ and $N_{\mathrm{PL,Rx}}$ are equal [60].

As a result of their respective definitions, TS and eqTS have the following properties.

1) TS is a function of (bistatic) angle and independent of position, whereas eqTS is a function of position and has no explicit angle dependence.
2) The reference values for TS and eqTS are 1 m^2/sr and 1 m^2, respectively [the latter follows by application of the multiplication rule to (48)].
3) For an isotropic scatterer, TS and eqTS are equal, in which case either may be used in the active sonar equation, without approximation. More generally, only eqTS results in a correct sonar equation.

G. Bioacoustics

1) Ambient Noise, Ambient Sound, and Soundscape: Two widely used terms in underwater acoustics are "ambient sound" and "ambient noise." They are sometimes used interchangeably but ISO 18405 distinguishes between them. The term "soundscape" is closely related to "ambient sound."

a) Ambient noise: The concepts of "signal" and "noise" are subjective. The sound of whale song is the sound of interest (i.e., the signal) to a conspecific, whereas to a human sonar operator, the same sound would be noise. The meaning of "ambient noise" is therefore also subjective because its use implies the existence of a signal being masked by ambient noise. The precise definition of "ambient noise" (entry 3.1.5.1) reads:

> "*sound* except *acoustic self-noise* and except sound associated with a specified *signal*"

b) Ambient sound: In the case of 'ambient sound' the entire sound field is potentially of interest. In this context, all sound (other than acoustic self-noise) may be considered signal. The term (entry 3.1.1.2) is formally defined as

> "*sound* that would be present in the absence of a specified activity"

The phrasing "in the absence of a specified activity" is primarily intended to exclude acoustic self-noise when the specified activity is the act of measurement, although the definition is general enough to exclude the sound from any other activity that is specified.

c) Soundscape: For airborne acoustics, in the context of human hearing, the term *soundscape* usually implies an element of perception of the sound. For example, entry 2.3 of ISO 12913-1:2014 [118] defines "soundscape" as "acoustic environment as perceived or experienced and/or understood by a person or people, in context." However, the same term is used without this implication in contexts other than human hearing, in air [119]–[121], and in water [122]–[124]. For this reason, the definition of "soundscape" according to ISO 18405:2017 [46] (entry 3.1.1.3) also excludes a perception element. It is the ambient sound after some qualitative interpretation. The related terms "auditory scene" and "auditory stream," although not defined by ISO 18405:2017 [46], are in use to describe the perception of a soundscape by a listener [125], [126].

2) Production of Sound:

a) Communication signals, echolocation clicks, and shrimp snaps: Sound production in aquatic fauna is common and highly varied. A small selection of such sounds is defined by ISO 18405:2017 [46], including drumming [127], snapping [128], grinding, and stridulation [129]. *Drumming* (entry

3.7.3.5) and *stridulation* (entry 3.7.3.6) are examples of *bioacoustic communication signals* (entry 3.7.3.2). The *echolocation clicks* (entry 3.7.3.3) of odontocetes (toothed whales), as their name implies, are used for distance finding and the clicks of some odontocetes are so intense that these are hypothesized to be used for stunning prey [130]–[132]. For example, the source waveform of a sperm whale click can exceed 800 kPa m.

Although the peak source waveform of the snapping shrimp's snap (3 kPa m) is 250 times smaller than that of the sperm whale click, the tiny shrimp also uses high intensity sound to stun or kill its prey [128]. The zero to peak sound pressure at a distance of one body length, of 16 m and 4 cm for the sperm whale and snapping shrimp, respectively, is of similar magnitude (and exceeds 50 kPa) for both animals.

b) Deliberations on "Phonation" and "Vocalization": Possible definitions for the terms "phonation" and "vocalization" were considered by WG2. In 2014, a proposal to define these terms, respectively, as "sound production that involves the use of a vocal organ" and "phonation that involves the use of vocal chords," was provisionally adopted in a working draft. These two entries were subsequently discussed and modified during a period exceeding a year and ultimately excluded from the standard due to lack of consensus for the proposed definitions.

3) Reception and Perception of Sound: Two fundamental concepts related to the perception of sound are those of hearing threshold and critical ratio (CR) (clause 3.7).

a) Thresholds of hearing: The standard includes two definitions of hearing threshold, one behavioral and one electrophysiological.

1) Behavioral thresholds reflect cognitive function, i.e., decisions, by the animal in response to an acoustic signal, which are used to determine thresholds. Behavior represents a holistic response, meaning it accounts for the peripheral auditory system response (at the ear), the collective central auditory system response (the brain), and a cognitive/motivation behavioral response (higher brain function) to the acoustic stimulus. To obtain behavioral thresholds, training of the animal is required, to have a predetermined response that indicates the stimulus was heard. The behavioral hearing threshold (entry 3.7.2.1) is defined as the lowest level of a specified acoustic stimulus eliciting a behavioral response in specified conditions. Trained responses often include touching a target or cardiac conditioning to indicate the stimulus was indeed heard. In simple terms, the animal informs the scientist whether the sound stimulus was heard.
2) Electrophysiological thresholds reflect neurophysiological responses (electrical impulses) of lower brain function in response to an acoustic signal, which is used to determine thresholds. To obtain electrophysiological thresholds, there is no need to train the animal. Instead a clinical approach is used to capture and measure an animal's neurophysiological responses. The electrophysiological hearing threshold (entry 3.7.2.2) is defined as the lowest level of a specified acoustic stimulus resulting in an *in situ* electrical response. For example, the electrophysiological threshold may be captured through a technique called auditory evoked potential, and in terrestrial animals where the electrical response is known to originate from the lower brain centers, it is called an auditory brainstem response. In general, the technique uses external electrodes to measure stereotypical electrical responses entrained to a sound stimulus. This technique measures the auditory system peripheral detection (from hair cells in the inner ear) and pathways to the brainstem.

b) Critical ratio (CR): The CR (entry 3.7.2.7) is defined in terms of the signal to noise ratio of a just detectable signal, and is closely related to the DT (entry 3.6.2.1). More precisely, it is the ratio of the signal power to the noise spectral density of white noise, in which the signal is just detectable. The relation between CR and DT is considered next.

In the following, the behavioral hearing threshold is considered because of its relevance to sound perception. The behavioral hearing threshold ($L_{p,\mathrm{bHT}}$) has implications for signal detection probability and signal excess. On the assumption in this context that only the signal varies, with noise held constant, the noise terms cancel in (43) leaving

$$\Delta L_{\mathrm{SE}} = L_{p,\mathrm{s}} - L_{p,\mathrm{bHT}}. \tag{51}$$

Thus, the signal excess is the amount by which (for fixed noise) the signal SPL exceeds $L_{p,\mathrm{bHT}}$.

When the signal excess is equal to 0 dB, the signal is said to be just detectable, which means that the probability of detection is equal to some specified minimum value (usually 50%). The standard requires that any value of hearing threshold be accompanied by the corresponding measurement conditions, although the conditions themselves are not standardized.

Equation (51) follows from (43) for masked hearing (hearing threshold limited by background noise). It is proposed as a generalization of (43) for unmasked hearing (hearing threshold unaffected by background noise).

If the hearing is masked, we can relate $L_{p,\mathrm{bHT}}$ to R_c from the definitions of these terms (clause 3.7) such that

$$10\log_{10}\frac{R_\mathrm{c}}{1\ \mathrm{Hz}}\ \mathrm{dB} = L_{p,\mathrm{bHT}} - L_{p,\mathrm{n},f}. \tag{52}$$

Rearranging for $L_{p,\mathrm{bHT}}$ and substituting into (51) gives

$$\Delta L_{\mathrm{SE}} = L_\mathrm{S} - N_{\mathrm{PL}} - L_{p,\mathrm{n},f} - 10\log_{10}\frac{R_\mathrm{c}}{1\ \mathrm{Hz}}\ \mathrm{dB}. \tag{53}$$

The CR is closely related to the DT used in the sonar equation, which is the difference between signal level and noise level of a just detectable signal, such that

$$\Delta L_{\mathrm{SE}} = L_\mathrm{S} - N_{\mathrm{PL}} - L_{p,\mathrm{n}} - \Delta L_{\mathrm{DT}}. \tag{54}$$

It is tempting to conclude from (53) and (54) that

$$\Delta L_{\mathrm{DT}} = 10\log_{10}\frac{R_\mathrm{c}}{1\ \mathrm{Hz}}\ \mathrm{dB} - (L_{p,\mathrm{n}} - L_{p,\mathrm{n},f}) \tag{55}$$

but the interpretation of this last equation is not straightforward because it implies a bandwidth associated with the receiver processing, whereas a biological receiver might not have a clearly defined processing bandwidth in the sense of the sonar equation.

Nevertheless, one possible interpretation is the auditory critical bandwidth B_{ac} such that

$$L_{p,\mathrm{n}} - L_{p,\mathrm{n},f} = 10\log_{10}\frac{B_{\mathrm{ac}}}{1\ \mathrm{Hz}}\ \mathrm{dB} \tag{56}$$

and in this interpretation, it follows (for masked hearing) that

$$\Delta L_{\mathrm{DT}} = 10\log_{10}\frac{R_{\mathrm{c}}}{B_{\mathrm{ac}}}\ \mathrm{dB}. \tag{57}$$

According to Au [133], the CR for human hearing in air exceeds the auditory critical band by a factor of 2.5, whereas for a bottlenose dolphin in water that ratio is 5.6. These ratios imply a DT of 4.0 dB for human hearing and 7.5 dB for dolphin hearing.

c) Weighted sound pressure and weighted sound exposure: Humans and other animals have a hearing sensitivity that varies with frequency, with frequency of best hearing depending on species. For humans, the full hearing range is approximately 20 Hz to 20 kHz, with the region of highest hearing sensitivity of 2–4 kHz in air [134] or 0.5–1 kHz in water [18], [135], [136]. Thus, when determining noise exposure standards and limits, the acoustic energy of a noise is filtered to reflect the human ear sensitivity and de-emphasize frequencies of low sensitivity. Three different auditory weighting functions are in use to reflect the frequency response of human hearing; A-, C-, and Z-weighting [137]. Each weighting emphasizes different frequency ranges, depending on the type of noise being considered.

The sound exposure metric can be frequency weighted. Weighted sound exposure (E_{w}) is defined as the integral of the squared weighted sound pressure [$p_{\mathrm{w}}(t)$] between a specified start time (t_1) and end time (t_2)

$$E_{\mathrm{w}} \equiv \int_{t_1}^{t_2} p_{\mathrm{w}}(t)^2 \mathrm{d}t. \tag{58}$$

In practice, the weighted sound exposure is usually calculated in the frequency domain by making use of Plancherel's theorem [see (5)]. Assuming a pulse of finite duration to extend the integration limits to infinity without approximation, this may be written as

$$E_{\mathrm{w}} = \int_{-\infty}^{+\infty} p_{\mathrm{w}}(t)^2\ \mathrm{d}t = 2\int_0^{+\infty} |P_{\mathrm{w}}(f)|^2 \mathrm{d}f \tag{59}$$

where $P_{\mathrm{w}}(f)$ is the Fourier transform of the weighted sound pressure $p_{\mathrm{w}}(t)$ (the output of a linear filter when the input is sound pressure). The weighted sound pressure spectrum is related via the sound pressure transfer function $H(f)$ to the (unweighted) sound pressure spectrum $P(f)$

$$P_{\mathrm{w}}(f) = H(f)\,P(f)$$

and $H(f)$ is the sound pressure transfer function. It follows that

$$E_{p,\mathrm{w}} = 2\int_0^{+\infty} w_{\mathrm{aud}}(f)\,|P(f)|^2 \mathrm{d}f \tag{60}$$

where $w_{\mathrm{aud}}(f)$ is the auditory weighting function defined as

$$w_{\mathrm{aud}}(f) \equiv |H(f)|^2. \tag{61}$$

Once $w_{\mathrm{aud}}(f)$ is known or specified, the weighted sound exposure is calculated using (60).

The weighted SEL is obtained by converting (59) to decibels in the usual way

$$L_{E,\mathrm{w}} = 10\log_{10}\frac{E_{\mathrm{w}}}{p_0^2 t_0}\ \mathrm{dB}. \tag{62}$$

d) Auditory frequency weighting functions: To determine potential adverse impacts on aquatic fauna, auditory frequency weighting functions can be used to adjust selected acoustic metrics by de-emphasizing contributions at frequencies of low sensitivity to sound. For most species of aquatic fauna, no widely recognized weighting functions are available.

Auditory weighting functions for marine mammals have been developed [76], [138], and use of the Finneran weighting functions [138] is recommended by US regulators [139] and by a panel of marine mammal hearing experts [77], [140]. While the weighting functions proposed by Finneran [138] are now widely accepted [77], [139], [141], the terminology used to describe them differs between publications (see Table VIII), which can lead to misinterpretation. The risk of misinterpretation can be reduced by adopting a standard terminology, and according to NMFS (2018) "ISO 18405 is the preferred [terminology] standard because it was developed specifically for underwater acoustics." Column 1 of Table VIII proposes terms compatible with ISO 18405.

a) M-Weighting: ISO 18405 mentions M-weighting [76] as an example of auditory frequency weighting function

$$w_{\mathrm{aud,M}}(f) = \frac{(1 + f_{\mathrm{lo}}/f_{\mathrm{hi}})^4}{(1 + f_{\mathrm{lo}}^2/f^2)^2(1 + f^2/f_{\mathrm{hi}}^2)^2} \tag{63}$$

where f_{lo} and f_{hi} are lower and higher auditory roll-off frequencies. The quantity $w_{\mathrm{aud,M}}(f)$ varies with frequency f and has a maximum value of 1 at $f = \nu_{\mathrm{M}}$, i.e.,

$$w_{\mathrm{aud,M}}(\nu_{\mathrm{M}}) = 1 \tag{64}$$

where ν_{M} is given by

$$\nu_{\mathrm{M}} = (f_{\mathrm{lo}} f_{\mathrm{hi}})^{1/2} \tag{65}$$

which is the geometric mean of the two roll-off frequencies.

b) Finneran Weighting: M-weighting has since been superseded by Finneran [138] weighting functions (published in [77]) of the form (see Table VIII)

$$w_{\mathrm{aud}}(f) = \left(\frac{1 + f_{\mathrm{lo}}^2/\nu^2}{1 + f_{\mathrm{lo}}^2/f^2}\right)^a \left(\frac{1 + \nu^2/f_{\mathrm{hi}}^2}{1 + f^2/f_{\mathrm{hi}}^2}\right)^b \tag{66}$$

where the frequency (ν) at which $w_{\mathrm{aud}}(f)$ reaches its maximum value is given by (see Table IX)

$$\nu^2 = \left(\frac{a}{b}\right)^{1/2} f_{\mathrm{lo}} f_{\mathrm{hi}} \left[\left(1 + \varepsilon^2\right)^{1/2} - \varepsilon\right] \tag{67}$$

where

$$\epsilon = \frac{f_{\mathrm{lo}}}{2f_{\mathrm{hi}}}\left(\frac{b}{a}\right)^{1/2}\left(1 - \frac{a}{b}\right). \tag{68}$$

If ϵ is small (and it is for all cases in Table IX), (67) and (66) simplify to

$$\nu^2 \approx \left(\frac{a}{b}\right)^{1/2} f_{\mathrm{lo}} f_{\mathrm{hi}} (1 - \epsilon) \tag{69}$$

TABLE VIII
PROPOSED TERMINOLOGY OF AUDITORY FREQUENCY WEIGHTING FUNCTIONS (COLUMN 1) COMPARED WITH TERMINOLOGY IN USE SINCE 2007 (COLUMNS 2–6)

Proposed name (symbol)	**Southall (2007)**	**Finneran (2016)**	**ISO 18405 (2017) See entry 3.7.1.7**	**NMFS (2018)**	**Southall (2019)**
Auditory frequency weighting function (w_{aud})	N/A	N/A	Auditory frequency weighting function (w_{aud})	N/A	N/A
Logarithmic auditory frequency weighting function (W_{aud})	Frequency-weighting function (M)	Weighting function amplitude (W)	N/A	Auditory weighting function (W_{aud})	Weighting function amplitude (W)
Lower auditory roll-off frequency (f_{lo})*	Lower functional hearing limit (f_{low})	Low-frequency cutoff (f_1)	Lower functional hearing limit (f_{low})	Low-frequency cutoff (f_1)	LF transition value (f_1)
Higher auditory roll-off frequency (f_{hi})*	Higher functional hearing limit (f_{high})	High-frequency cutoff (f_2)	Higher functional hearing limit (f_{high})	High-frequency cutoff (f_2)	HF transition value (f_2)
Low frequency weighting function exponent (a)*	N/A	Low frequency exponent (a)	N/A	Low frequency exponent (a)	LF exponent value (a)
High frequency weighting function exponent (b)*	N/A	High frequency exponent (b)	N/A	High frequency exponent (b)	HF exponent value (b)

*See Table IX.

TABLE IX
SOUTHALL ET AL. [77] HEARING GROUPS

Marine mammal hearing group	f_{lo} / kHz	f_{hi} / kHz	a	b	ε	ν /kHz
Low-frequency cetaceans (LF)	0.20	19	1.0	2.0	0.00372	1.64
High-frequency cetaceans (HF)	8.80	110	1.6	2.0	0.00894	29.29
Very high-frequency cetaceans (VHF)	12.00	140	1.8	2.0	0.00452	39.83
Sirenians (SI)	4.30	25	1.8	2.0	0.00907	10.05
Phocid carnivores in water (PCW)	1.90	30	1.0	2.0	0.02239	6.28
Other marine carnivores in water (OCW)	0.94	25	2.0	2.0	0	4.85

The roll-off frequencies ($f_{\mathrm{lo}},\ f_{\mathrm{hi}}$) and weighting function exponents (a,b) are from Table 5 of [77]. The remaining two columns (ε , $\boldsymbol{\nu}$) are from (68) and (67), respectively.

and

$$w_{\mathrm{aud}}\left(f\right) \approx \frac{\left(1+f_{\mathrm{lo}}/f_{\mathrm{hi}}\right)^{2\sqrt{ab}}}{\left(1+f_{\mathrm{lo}}^2/f^2\right)^a\left(1+f^2/f_{\mathrm{hi}}^2\right)^b} \tag{70}$$

respectively. The right-hand side of (70) is exactly equal to the weighting function w_{aud} (66) when a and b are equal [e.g., with Finneran weighting for OCW, or with M-weighting (63)], and within 0.04% of w_{aud} for all cases in Table IX.

The quantity described by Southall *et al*. [77] is the logarithmic auditory frequency weighting function (which we denote here by the symbol W_{aud}, with upper case W). This quantity is obtained from the auditory frequency weighting function (denoted here by the symbol w_{aud}, with *lower* case w, following ISO 18405) by

$$W_{\mathrm{aud}}\ \left(f\right) = \ 10\log_{10} w_{\mathrm{aud}}\left(f\right)\ \mathrm{dB}. \tag{71}$$

Standardizing the terminology used to develop and define these weighting functions will help improve the understanding and application of these weighting functions.

H. Errata

The authors are aware of four typographical errors in ISO 18405:2017, hereby corrected.

1) In clause 0.4, "target strength (reference value = 1 m^2) … become 1 m" should read "target strength (reference value = 1 m^2 sr^{-1}) … become 1 m sr$^{-1/2}$."
2) In Table 1, the reference value of propagation factor is 1 m^{-2} (not 1 m^2), and the reference value of root-propagation factor is 1 m^{-1} (not 1 m).
3) In note 4 to entry 3.1.5.7, "$F\ (t) = F_0\ \cos(kx - \omega t + f)$, where ϕ is a constant phase, the analytic representation of $F(t)$ is $\tilde{F}\ (t) = F_0\ \exp(\mathrm{i}kx - \mathrm{i}\omega t + \mathrm{i}\phi)$" should read "$F\ (t) = F_0\ \cos(\omega t - kx + \phi)$, where ϕ is a constant phase, the analytic representation of $F(t)$ is $\tilde{F}\ (t) = F_0\ \exp(\mathrm{i}\omega t - \mathrm{i}kx + \mathrm{i}\phi)$."
4) The definition of "active sonar equation" (entry 3.6.2.11) contains a typographical and a factual error. There is no approximation in the closing equation, which should also contain no comma. Correcting both, the text "the approximation $10\,\lg R_{\mathrm{SN}}\ \mathrm{dB}, \approx L_{\mathrm{S}} - N_{\mathrm{PL,Tx}} + N_{\mathrm{TS,eq}} -$

$N_{\mathrm{PL,Rx}} - L_{\mathrm{N}} + \Delta L_{\mathrm{PG}}$" should read "the formula $10\ \lg R_{\mathrm{SN}}\ \mathrm{dB} = L_{\mathrm{S}}\ - N_{\mathrm{PL,Tx}} + N_{\mathrm{TS,eq}} - N_{\mathrm{PL,Rx}} - L_{\mathrm{N}} + \Delta L_{\mathrm{PG}}$."

III. Discussion

A. Recent Changes to ISO/IEC 80000

ISO 80000-3 *Quantities and Units – Space and Time* and ISO 80000-8 *Quantities and Units – Acoustics* were revised in 2019 and 2020, respectively. The most important changes in terms of their impact on ISO 18405 are summarized as follows.

1) Reference Values: When ISO/IEC 80000 was finalized in 2009, it defined SPL exclusively using the in-air reference sound pressure of 20 μPa, making it inapplicable to underwater acoustics and effectively placing all levels used in underwater acoustics, including those defined in ISO 18405, outside the ISQ. The 2020 revision of Part 8 recognizes 1 μPa and 1 $\mu\mathrm{Pa}^2\mathrm{s}$ as legitimate alternatives to 20 μPa and 400 $\mu\mathrm{Pa}^2\mathrm{s}$, respectively, making ISO 18405 compatible with the ISQ.

2) Omission of Decibel: The definition of the decibel in the ISQ and its predecessors went essentially unchanged from 1978 to 2019. That longstanding definition was omitted from the 2019 revision of ISO 80000-3, with the result that the ISQ at the time of writing does not include a definition of the decibel (but see Appendix B-D)

The ISO 18405 definitions of basic terms such as SPL, sound power level, and SEL are all expressed explicitly in terms of the decibel. Without a definition of the decibel, the definitions of all these levels are incomplete. The history of the decibel is therefore summarized in Appendix B.

B. Gaps in Standard Underwater Acoustical Terminology

While ISO 18405 provides basic acoustical terminology on which to build, ongoing sound monitoring projects have found it necessary to develop new terminology [83], [142] to describe the associated hardware, digital acquisition, data processing, acoustic source and propagation modeling, and the outputs of these processes [83], [142], [143], including particle motion [144]. An international standard would facilitate effective interproject communication for programs associated with the EU's Marine Strategy Framework Directive [145], [146] or the US Ocean Noise Strategy [147]. Also needed is the terminology with which to describe animals' production and reception of underwater sound. Examples of specific terms that need definition might include "hearing," "impulsive sound," and "continuous sound."

C. Closing Remarks

Ambiguity exists when we communicate concepts in underwater acoustics, as in any scientific discipline, if we do not precisely define the terms used. While terminology could in principle be redefined in each new publication, this rarely happens, and amounts to a waste of resources when an international standard could simply be cited. This article describes the first international standard for underwater acoustical terminology. The standard ISO 18405:2017 facilitates effective communication for describing underwater soundscapes, sound radiation and reception, and sound propagation and scattering. As a community, we can improve interdisciplinary communications for acoustics by following international standards and being consistent in meaning and intent of terms.

Appendix A
2010 Letter From ASA Standards Director

In 2010, the ASA proposed the creation of an ISO subcommittee on underwater acoustics within technical committee TC 43 (Acoustics) (see Fig. 1). The proposal ultimately led to the creation of TC 43/SC 3 Underwater Acoustics, which held its inaugural meeting at Woods Hole in June 2012.

Appendix B
Decibel: Past, Present, and Future

In underwater acoustics, the concept of level is widely used, and level is normally expressed in decibels. Many ISO 18405 definitions, e.g., of SPL, are written explicitly in terms of the decibel. Such definitions are incomplete unless the decibel is also defined. An appropriate definition of the decibel is therefore part of the foundations of ISO 18405, which relies on the definition of the decibel from the ISQ (ISO 80000-3:2006 [28]). This appendix tracks the history of the decibel from its introduction in 1928 to the present, pointing out the absence from the ISQ, since 2019, of a definition of this unit, and the implications of this absence for ISO 18405.

A. Introduction of the Decibel and AStA Standards (1928–1951)

Hartley [148] introduced the decibel as a logarithmic unit of power ratio equal to one-tenth of a bel, where the number of bels corresponding to the power ratio $Q_{P,1}/Q_{P,2}$ is $\log_{10}(Q_{P,1}/Q_{P,2})$. This definition was formalized by AStA in 1942 [8] based on AStA (1941) [149] (see Fig. 2), and updated in 1951 [10], with only minor changes.

B. ANSI Standards (1960–2013)

In 1960, ANSI introduced a new definition of the decibel [11], which in essence remains unchanged today [20], [24]. The modern ANSI standard [24] defines the decibel as the "unit of the level of a power or power-like quantity when the base of the logarithm is the tenth root of ten," where the level L_P of a power quantity Q_P is [65]

$$L_P \equiv \log_\beta \frac{Q_P}{Q_{P,0}}\ [L_P] \tag{72}$$

and $[L_P]$ is the unit of the quantity L_P (ISO 80000-1), which depends on base β. It follows from (72) and the ANSI definition that

$$L_P = \log_{10^{0.1}} \frac{Q_P}{Q_{P,0}}\ \mathrm{dB} \tag{73}$$

from which (8) follows. Thus, (73) becomes a consequence of the ANSI definition, instead of the defining equation.

Acoustical Society of America

OFFICE OF THE
STANDARDS DIRECTOR

Paul D. Schomer, Ph.D.
Standards Director

2117 Robert Drive, Champaign, IL 61821

Telephone (217) 359-6602
Fax (217) 359-3303
E-mail schomer@SchomerAndAssociates.com

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.

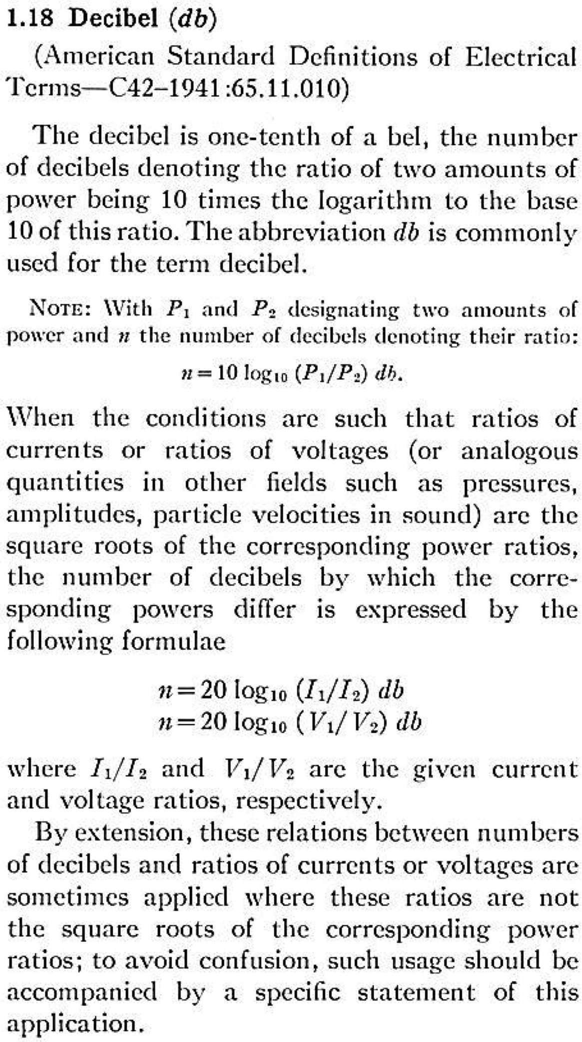
Fig. 1. 2010 letter from ASA Standards Director, P. Schomer, to ASA Technical Committees on Acoustical Oceanography, Animal Bioacoustics and Underwater Acoustics.

C. International System of Quantities (ISQ) (1978–Present)

The first international standard known to the authors to define the decibel is ISO 31-7:1978 [149], which defined sound power level as $0.5\ \log_{\mathrm{e}}(W/W_0)\ \mathrm{Np}$, with W the sound power and W_0 its (then unspecified) reference value. The same standard defined the decibel as the value of sound power level when $10\ \log_{10}\ (W/W_0) =\ 1$. It followed from these two definitions that $1\,\mathrm{dB}\ =\ 0.05\log_{\mathrm{e}}10\,\mathrm{Np}$ [1]. With minor variants, including the introduction of a standard reference sound power of $W_0 = 1\ \mathrm{pW}$, the same definition was repeated in ISO 31-7:1992 [61] and ISO 80000-3:2006 [28]. ISO 80000-3:2006 [28] included definitions of *level of a field quantity*, *level of a power quantity*, *bel,* and *decibel*. The 2019 revision of this standard [29] omits these terms.

D. Present Status and Future of the Decibel

The absence of a definition of the decibel from ISO 80000-3:2019 means that all definitions in ISO 18405 cast in terms of the decibel, such as that of SPL, are incomplete. A new ISQ standard (IEC 80000-15) is under development that is expected



1.18 Decibel (*db*)

(American Standard Definitions of Electrical Terms—C42–1941:65.11.010)

The decibel is one-tenth of a bel, the number of decibels denoting the ratio of two amounts of power being 10 times the logarithm to the base 10 of this ratio. The abbreviation *db* is commonly used for the term decibel.

NOTE: With P_1 and P_2 designating two amounts of power and n the number of decibels denoting their ratio:

$$n = 10 \log_{10} (P_1/P_2) \; db.$$

When the conditions are such that ratios of currents or ratios of voltages (or analogous quantities in other fields such as pressures, amplitudes, particle velocities in sound) are the square roots of the corresponding power ratios, the number of decibels by which the corresponding powers differ is expressed by the following formulae

$$n = 20 \log_{10} (I_1/I_2) \; db$$
$$n = 20 \log_{10} (V_1/V_2) \; db$$

where I_1/I_2 and V_1/V_2 are the given current and voltage ratios, respectively.

By extension, these relations between numbers of decibels and ratios of currents or voltages are sometimes applied where these ratios are not the square roots of the corresponding power ratios; to avoid confusion, such usage should be accompanied by a specific statement of this application.

Fig. 2. Description of "decibel" from AStA (1942) [8], using the symbol "db," with a lower case "b." By 1969, the accepted symbol had become "dB" [43].

to provide a replacement definition of *decibel*. In the meantime, the main alternatives to consider are the IEC [150] and ANSI [24] standards already mentioned and an earlier IEC standard IEC [21], similar to the ANSI standard.

If a definition is needed before the publication of IEC 80000-15, the authors recommend following ANSI [24] for the definition of *decibel*, combined with the definition of level from (72) [65].

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Michael Ainslie is a Senior Scientist with JASCO Applied Research, in Germany and a Visiting Professor with the Institute of Sound and Vibration Research, University of Southampton, in U.K. He received degrees in physics from Imperial College, United Kingdom, in 1981 and mathematics from the University of Cambridge, United Kingdom, in 2011, and the Ph.D. degree in seabed acoustics from the University of Southampton, United Kingdom, in 1991. He has authored the book Principles of Sonar Performance Modeling (Springer, 2010), and his research interests include sonar performance modeling and effects of sound on aquatic life. He is Convenor of the ISO working group ISO/TC 43/SC 3/WG 2 (Underwater Acoustical Terminology), and a founding member of the EU expert group Technical Group Noise.

Michele Halvorsen is a Research Associate Professor with the University of New Hampshire. She received a bachelor's degrees in zoology from Southern Illinois University, United States, in 1991 and a Ph.D. degree in neurophysiology from the University of Illinois, Chicago, in 2003. She has carried out multiple studies measuring barotrauma effects of impulsive signals on fish tissues and is coauthor of Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Her research interests include the effects of high amplitude sound on fishes. She Chairs the Marine Bioacoustical Standardization Working Group of the International Quiet Ocean Experiment and is a member of the ISO Working Group ISO/TC 43/SC 3/WG 2 (Underwater Acoustical Terminology).

Stephen P. Robinson is a Principal Research Scientist and Technical Lead in underwater acoustic metrology with the U.K National Physical Laboratory. He received a degree in physics from the University of Manchester, United Kingdom, in 1985. He has coauthored multiple international standards for measurement of underwater sound and calibration of instrumentation, and his research interests include long-term trends in ambient sound. He is the Chair of the ISO Sub-Committee 3 on underwater acoustics of ISO/TC 43 and Convenor of the international standards working groups ISO/TC 43/SC 3/WG 3 (Pile driving) and IEC/TC 87/WG 15 (Calibration in Underwater Acoustics), and was a founding member of the EU expert group Technical Group Noise.