National Oceanic and Atmospheric Administration



DRAFT Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing

Underwater Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts

Revised version for Second Public Comment Period

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ACRONYMS AND SYMBOLS

a	Low-frequency exponent
ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
ANSI	American National Standards Institute
b	High-frequency exponent
C	Weighting function gain (dB)
cm	centimeter
CT	Computerized Tomography
D	Duty Cycle
dB	Decibel
dB_{peak}	Peak sound pressure level
dB_{p-p}	Peak-to-peak sound pressure level
dB_{rms}	Root mean square sound pressure level
DPOAE	Distortion product otoacoustic emission
E_0	Exposure Threshold
EEH	Equal Energy Hypothesis
EQL	Equal Loudness
ES	Executive Summary
ESA	Endangered Species Act
f_0	Best hearing (kHz)
f_1	Low-frequency cutoff (kHz)
f_2	High-frequency cutoff (kHz)
H	Water depth
h	hour
HF	High-frequency
HISA	Highly Influential Scientific Assessment
Hz	Hertz
in	Inch
in^3	Cubic Inches
ISI	Influential Scientific Information
IQG	Information Quality Guidelines
ITA	Incidental Take Authorizations
K	Exposure function gain (dB)
kg	kilogram
kHz	Kilohertz
LF	Low-frequency
L_{pk}	Peak sound pressure level
L_E	Sound exposure level
MF	Mid-frequency
min	Minutes
MMC	Marine Mammal Commission
MMPA	Marine Mammal Protection Act
MSA	Magnuson-Stevens Fishery Conservation and Management Act
MSE	Mean-squared error
m	meter
ms	Milliseconds
NITS	Noise-induced Threshold Shift
NMFS	National Marine Fisheries Service
NMSA	National Marine Sanctuaries Act
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	National Research Council
NS2	National Standard 2
OMB	Office of Management and Budget
ONMS	Office of National Marine Sanctuaries
OSHA	Occupational Safety and Health Administration
OW	Otariids in water
Pa	Pascals
π	pi

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psi	Pound per square inch
PTS	Permanent Threshold Shift
PW	Phocids in water
R	Range
R_0	Safe Distance
R^2	Goodness of fit
RL	Received Level
RMS	Root Mean Square
S	Source Factor
S_E	Energy Source Factor
s	Seconds
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SL	Source Level
s_0	Slope (dB/decade)
SPL	Sound Pressure Level
SSC	Space and Naval Warfare Systems Center
τ	Repetition Time
TAP	U.S. Navy's Tactical Training Theater Assessment and Planning Program
TS	Threshold Shift
TTS	Temporary Threshold Shift
µPa	Micropascal
μPa^2-s	Micropascal squared second
USFWS	U.S. Fish and Wildlife Service
v	Velocity
VSP	Vertical Seismic Profiling
$W(f)$	Weighting function
w	Charge weight

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EXECUTIVE SUMMARY

This document provides guidance for assessing the effects of anthropogenic (human-made) sound on marine mammal species under the jurisdiction of the National Marine Fisheries Service (NMFS) and the National Ocean Service (NOS) (hereafter referred to collectively as the National Oceanic and Atmospheric Administration (NOAA)). Specifically, it identifies the received levels, or acoustic threshold levels, above which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources. This is the first time NOAA has presented this information in a single, comprehensive document. This guidance is intended for use by NOAA analysts and managers and other relevant action proponents and stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in impacts to marine mammal hearing via acoustic exposure. This document outlines NOAA's updated acoustic threshold levels and describes in detail how the thresholds were developed and how they will be updated in the future.

NOAA has compiled, interpreted, and synthesized the best available science, including a recent Navy Technical Report (Finneran 2015), to produce updated acoustic threshold levels for the onset permanent threshold shifts (PTS) (Table ES1) and replace those currently in use by NOAA for determining PTS. Updates include a protocol for estimating PTS onset threshold levels for impulsive (e.g., airguns, impact pile drivers) and non-impulsive (e.g., sonar, vibratory pile drivers) sound sources, the formation of marine mammal functional hearing groups (low-, mid-, and high-frequency cetaceans, and otariid and phocid pinnipeds), and the incorporation of marine mammal auditory weighting functions into the calculation of PTS threshold levels. These acoustic threshold levels are presented using dual metrics of cumulative sound exposure level and peak sound pressure level. This document addresses how to combine multiple datasets, as well as how to determine appropriate surrogates when data are not available. While the updated acoustic threshold levels are more complex than those previously used by NOAA, they reflect the current state of scientific knowledge regarding the characteristics of sound that have the potential to impact marine mammal hearing sensitivity. Given the specific nature of these updates, it is not possible to compare the updated acoustic threshold levels presented in this document with the thresholds previously used by NOAA (i.e., difficult to generalize for all possible scenarios because outcome would depend on project-specific specifications).

Although NOAA has updated the acoustic threshold levels from those previously used, and these changes may necessitate new methodologies for calculating impacts, the application of the thresholds under applicable statutes (Marine Mammal Protection Act, Endangered Species Act, and National Marine Sanctuaries Act) remains consistent with past NOAA practice. These updated PTS acoustic threshold levels do not represent the entirety of the comprehensive effects analysis, but rather serve as one tool (e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the ultimate effects of any particular type of impact on an individual's fitness, population assessments, etc.) to help evaluate the effects of a proposed action on marine mammal hearing and make findings required by NOAA's various statutes.

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This Guidance is classified as a Highly Influential Scientific Assessment by the President's Office of Management and Budget. As such, independent peer review was required prior to broad public dissemination by the Federal Government. Details of the three peer reviews, associated with the Guidance, are within this document (Appendix D), and at the following website: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

Table ES1: Summary of PTS onset dual metric acoustic threshold levels.

	PTS Onset Threshold Levels (Received Level)	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* 230 dB_{peak} **&** 192 dB SEL_{cum}	*Cell 2* 230 dB_{peak} **&** 207 dB SEL_{cum}
Mid-Frequency (MF) Cetaceans	*Cell 3* 230 dB_{peak} **&** 187 dB SEL_{cum}	*Cell 4* 230 dB_{peak} **&** 199 dB SEL_{cum}
High-Frequency (HF) Cetaceans	*Cell 5* 202 dB_{peak} **&** 154 dB SEL_{cum}	*Cell 6* 202 dB_{peak} **&** 171 dB SEL_{cum}
Phocid Pinnipeds (Underwater)	*Cell 7* 230 dB_{peak} **&** 186 dB SEL_{cum}	*Cell 8* 230 dB_{peak} **&** 201 dB SEL_{cum}
Otariid Pinnipeds (Underwater)	*Cell 9* 230 dB_{peak} **&** 203 dB SEL_{cum}	*Cell 10* 230 dB_{peak} **&** 218 dB SEL_{cum}

* Dual metric acoustic threshold levels: Use whichever level [dB_{peak} or dB SEL_{cum}] exceeded first. All SEL_{cum} acoustic threshold levels (re: 1 μPa^2-s) incorporate marine mammal auditory weighting functions, while peak pressure thresholds should not be weighted. Note: Acoustic threshold levels for impulsive or non-impulsive sources are based on temporal characteristics at the source and not the receiver.

The SEL_{cum} could be exceeded in multitude of ways (i.e., varying exposure levels and durations, duty cycle). It is valuable for action proponents, if possible, to indicate under what conditions these acoustic threshold levels will be exceeded.

Note: In this Table, dB_{peak}, is equivalent to the ANSI abbreviation of L_{pk} and SEL_{cum} is equivalent to the ANSI abbreviation of L_E (ANSI 2013).

This document is organized so that the most pertinent information can be found easily in the main body. Additional details are provided in the appendices. Section I introduces the document and a description of how NOAA addressed uncertainty and data limitations in the development of this guidance. NOAA's updated acoustic threshold levels for onset of PTS for marine mammals exposed to underwater sound are presented in Section II. Section III describes how acoustic threshold levels are interpreted under NOAA's statutes. NOAA's plan for periodically updating acoustic threshold levels is presented in Section IV. More details on the development of acoustic threshold levels, the peer review and public comment process, research recommendations, and a glossary of acoustic terms are found in the appendices.

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION DRAFT GUIDANCE FOR ASSESSING THE EFFECTS OF ANTHROPOGENIC SOUND ON MARINE MAMMAL HEARING

UNDERWATER ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT AND TEMPORARY THRESHOLD SHIFTS

I. INTRODUCTION

This document provides guidance for assessing the effects of anthropogenic (human-made) sound on marine mammal species under the jurisdiction[1] of the National Marine Fisheries Service (NMFS) and the National Ocean Service (NOS) (hereafter referred to collectively as the National Oceanic and Atmospheric Administration (NOAA)). Specifically, it identifies the received levels, or threshold levels, above which individual marine mammals are predicted to experience changes in their hearing sensitivity for acute, incidental exposure to all underwater anthropogenic sound sources. This guidance is intended to be used by NOAA analysts and managers and other relevant action proponents and stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in impacts to marine mammal hearing via acoustic exposure. This document outlines NOAA's updated acoustic threshold levels and describes in detail how the thresholds were developed and how they will be revised and updated in the future.

The updated acoustic threshold levels presented in this document do not represent the entirety of the comprehensive effects analysis, but rather serve as one tool (e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the ultimate effects of any particular type of impact on an individual's fitness, population assessments, etc.), to help evaluate the effects of a proposed action on marine mammal hearing and make findings required by NOAA's various statutes. Note: This document does not directly address mitigation and monitoring measures that may be associated with particular activities.

This Guidance is classified as a Highly Influential Scientific Assessments (HISA)[2] by the President's Office of Management and Budget (OMB); as such, independent peer review was required before it could be disseminated more broadly by the Federal Government. As such, the Guidance underwent three independent peer reviews. NOAA also sought informal input

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[1] http://www.nmfs.noaa.gov/pr/species/mammals/. This document does not pertain to marine mammal species under the U.S. Fish and Wildlife Service's jurisdiction (e.g., walrus, polar bears, manatees, sea otters).

[2] Its dissemination could have a potential impact of more than $500 million in any one year on either the public or private sector; or that the dissemination is novel, controversial, or precedent-setting; or that it has significant interagency interest (OMB 2005).

from key federal agencies regarding various aspects of this document in early stages of its development.

1.1 NEED FOR GUIDANCE AND UPDATED UNDERWATER ACOUSTIC THRESHOLD LEVELS

Prior to this Guidance, NOAA primarily relied on two generic threshold levels for assessing auditory impacts (i.e., permanent threshold shift [PTS] onset) for most underwater sound sources: one for cetaceans (180 dB_{rms}), and one for pinnipeds (190 dB_{rms}). These generic thresholds were developed in the late 1990s using the best information available at the time (e.g., NOAA 1998; HESS 1999). Other sound sources, like tactical sonar and underwater explosives, have relied on more recently developed acoustic threshold levels (e.g., Finneran and Jenkins 2012; NOAA 2014). Since the adoption of these original thresholds, the understanding of the effects of noise on marine mammal hearing has greatly advanced (e.g., Southall et al. 2007) making it necessary to re-examine the current state of science and our acoustic threshold levels.

For this document, NOAA has compiled, interpreted, and synthesized the best available science on the impacts of sound on marine mammal hearing, including a recent Navy Technical Report (Finneran 2015), to produce updated underwater acoustic threshold levels for the onset of PTS. These threshold levels are intended to replace all those currently in use by NOAA for assessing PTS, including previously used generic injury thresholds and PTS/temporary threshold shift (TTS[3]) threshold levels for explosives and tactical sonar. While the updated acoustic thresholds are more complex than those previously used by NOAA, they reflect the current state of scientific knowledge regarding the characteristics of sound that have the potential to impact marine mammal hearing sensitivity.

This document does not provide updated acoustic threshold levels for non-auditory injury (i.e., lung injury or gastrointestinal tract injury) from underwater explosives, exposure to airborne sounds for pinnipeds, or levels that could result in behavioral effects. NOAA's current acoustic threshold levels for these impacts should remain in use until updated guidance can be completed.

This is the first time NOAA has presented this information in a single, comprehensive document, which can be used by NOAA analysts and managers and other relevant action proponents and stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in auditory impacts to marine mammals via acoustic exposure.

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[3] There may be some situations where determination of TTS onset may be necessary, and in those situations, the TTS acoustic threshold levels provided in this document (Appendix A, Table 10) should be used.

1.1.1 Updated Acoustic Threshold Levels within the Context of the Comprehensive Effects Analysis

As mentioned, the updated acoustic threshold levels presented in this document do not represent the entirety of the comprehensive effects analysis, but rather serve as one tool to help evaluate the effects sound produced during a proposed action on marine mammals and make findings required by NOAA's various statutes. In the regulatory context, NOAA uses acoustic threshold levels to help quantify "take" and to conduct more comprehensive effects analyses under several statutes.

Specifically, the acoustic threshold levels will be used in conjunction with sound source characteristics, environmental factors that influence sound propagation, anticipated marine mammal occurrence and behavior near the activity, as well as other available activity-specific factors, to estimate the number of takes of marine mammals. Thus, a multitude of factors is considered when calculating takes. This document only addresses threshold levels (i.e., does not address or make recommendations associated with sound propagation or marine mammal occurrence or density). For more information on how updated acoustic thresholds levels are applied within a regulatory context, see Section III.

1.2 Addressing Uncertainty and Data Limitations

Inherent data limitations occur in many instances when assessing acoustic effects on marine mammal hearing. Data limitations, which make it difficult to account for uncertainty and variability, are not unique to assessing the effects of anthropogenic sound on marine mammals and are commonly encountered by resource managers (Ludwig et al. 1993; Francis and Shotton 1997; Harwood and Stokes 2003; Punt and Donovan 2007). Southall et al. (2007) and Finneran (2015) acknowledged the inherent data limitations when making scientific recommendations for criteria to assess the effects of noise on marine mammals, including data available from a limited number of species, a limited number of individuals within a species, and/or limited number of sound sources. Both applied certain extrapolation procedures to estimate effects that had not been directly measured but that could be reasonably approximated using existing information and reasoned logic. Where NOAA has faced such uncertainty and variability in the development of its acoustic threshold levels, it is articulated the Guidance's extrapolation methodology.

1.2.1 Assessment Framework

NOAA's approach applies a set of assumptions to develop a framework that addresses uncertainty in predicting potential auditory effects of sound on individual marine mammals. One of these assumptions includes the use of "representative" or surrogate individuals/species for establishing PTS onset acoustic threshold levels for species where little to no data exists. The use of representative individuals/species is done as a matter of practicality (i.e., it is unlikely that adequate data will exist for the all marine mammal species found worldwide or that we will be able to account for all sources of variability at an

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individual level) but is also scientifically based (i.e., taxonomy, functional hearing group). As new data become available for more species, this approach will be reevaluated. NOAA recognizes that additional applicable data may become available to address better many of these issues. As these new data become available, NOAA has an approach for updating acoustic threshold levels (see Section IV).

1.2.2 Data Standards

In assessing potential acoustic effects on marine mammals, as with any such issue facing the agency, standards for determining applicable data need to be articulated. Specifically, NOAA has Information Quality Guidelines[4] (IQG) for "ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency" (with each of these terms defined within the IQG). Furthermore, the IQG stipulate that "To the degree that the agency action is based on science, NOAA will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods."

The National Research Council (NRC 2004) provided basic guidelines on National Standard 2 (NS2) under the Magnuson-Stevens Fishery Conservation and Management Act, section 301, which stated, "Conservation and management measures shall be based upon the best scientific information available" (NOAA 2013a). They recommended that data underlying the decision-making and/or policy-setting process be: 1) relevant, 2) inclusive, 3) objective, 4) transparent and open, 5) timely, 6) verified and validated, and 7) peer reviewed[5]. Although NRC's guidelines (NRC 2004) were not written specifically for marine mammals and this particular issue, they do provide a means of articulating minimum data standards. NOAA considered this in assessing acoustic effects on marine mammals. Use of the NRC Guidelines does not preclude development of acoustic-specific data standards in the future.

II. NOAA'S ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT THRESHOLD SHIFTS IN MARINE MAMMALS

This document advances NOAA's assessment ability based upon the compilation, interpretation, and synthesis of the best available science. As described in detail in this section, this includes both quantitative and qualitative approaches. Quantitative assessment consists of two parts: 1) an acoustic threshold level and 2) an associated auditory weighting function based upon marine mammal composite audiograms, equal latency, and data on

[4] http://www.st.nmfs.noaa.gov/science-quality-assurance/national-standards/ns2_revisions.

[5] NOAA also requires Peer Review Plans for Highly Influential Scientific Assessments (HISA) and Influential Scientific Information (ISI).

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susceptibility to noise-induced hearing loss (Finneran 2015). Additionally, qualitative considerations that illustrate general trends associated with noise-induced hearing loss are provided and may be useful within the comprehensive effects analysis, even though they cannot be applied quantitatively.

This document provides acoustic threshold levels for the onset of PTS based on characteristics defined at the source, as well as how those characteristics change with increasing distance from the source based on propagation. No direct measurements of marine mammal PTS has been published; PTS onset threshold levels have been extrapolated from marine mammal TTS measurements (i.e., using growth rates from terrestrial and marine mammal data). PTS onset acoustic threshold levels, for all sound sources, are divided into two broad categories: 1) impulsive and 2) non-impulsive. Acoustic threshold levels are also presented as dual metric acoustic threshold levels using cumulative sound exposure level (SEL_{cum}) and peak pressure (dB_{peak}) metrics. As dual metrics, NOAA considers onset of PTS to have occurred when either one of the two metrics is exceeded. Additionally, to account for the fact that different species groups use and hear sound differently, acoustic threshold levels in the SEL_{cum} metric are sub-divided into five broad functional hearing groups (i.e., low-, mid-, and high-frequency cetaceans and phocid and otariid pinnipeds) and incorporate auditory weighting functions.

2.1 MARINE MAMMAL FUNCTIONAL HEARING GROUPS

Current data (via direct behavioral and electrophysiological measurements) and predictions (based on inner ear morphology, modeling, behavior, vocalizations, or taxonomy) indicate that not all marine mammal species have equal hearing capabilities, in terms of absolute hearing sensitivity and the frequency band of hearing (Richardson et al. 1995; Wartzok and Ketten 1999; Southall et al. 2007; Au and Hastings 2008). Hearing has been directly measured in some of odontocete and pinniped species[6] (see review in Southall et al. 2007; Finneran 2015). Direct measurements of mysticete hearing are lacking (e.g., there was an unsuccessful attempt to directly measure hearing in a stranded gray whale calf by Ridgway and Carder 2001). Thus, hearing predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001; Parks et al. 2007; Ketten and Mountain 2011; Ketten and Mountain 2014; Ketten 2014; Cranford and Krysl 2015); vocalizations[7] (see reviews in Richardson et al. 1995; Wartzok and Ketten 1999; Au and Hastings 2008); and taxonomy and behavioral responses to sound (Dahlheim and Ljungblad 1990; see review in Reichmuth 2007).

To better reflect marine mammal hearing capabilities, Southall et al. (2007) recommended that marine mammals be divided into functional hearing groups based on measured or

[6] Hearing measurements both in air and underwater have been collected for pinniped species.

[7] Studies in other species indicate that perception of frequencies may be broader than frequencies produced (e.g., Luther and Wiley 2009).

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estimated functional hearing ranges[8]. NOAA modified the functional hearing groups proposed by Southall et al. (2007)[9] as follows:

- Extension of upper end of low-frequency cetacean hearing range: NOAA extended slightly the estimated upper end of the hearing range for low-frequency cetaceans, from 22 to 25 kHz, based on data from Watkins et al. (1986) for numerous mysticete species (variety of mysticete species[10] responding to sounds up to 28 kHz), Au et al. (2006) for humpback whales (songs having harmonics that extend beyond 24 kHz, which could indicate the potential to hear these higher frequencies), and a model (Tubelli et al. 2012) for minke whales (predicted hearing range of up to 25 kHz based on inner ear anatomy). These new data indicate that some mysticete species may have the potential hear above the 22 kHz proposed by Southall et al. 2007. Stronger datasets would help confirm this assumption. As more data become available[11], these estimated hearing ranges may require future modification or it may be necessary to subdivide the LF cetacean functional hearing group (e.g., Ketten 1997; Ketten et al. 2013).

- Division of pinnipeds into phocids and otariids and modification of hearing range: NOAA subdivided pinnipeds into their two families: Phocidae and Otariidae. Based on a review of the literature, phocid species have consistently demonstrated an extended frequency range of hearing compared to otariids, especially in the higher frequency range (Hemilä et al. 2006; Kastelein et al. 2009; Reichmuth et al. 2013). This is believed to be because phocid ears are anatomically distinct from otariid ears in that phocids have larger, more dense middle ear ossicles, inflated auditory bulla, and larger portions of the inner ear (i.e., tympanic membrane, oval window, and round window), which make them more adapted for underwater hearing (Terhune and Ronald 1975; Schusterman and Moore 1978; Kastak and Schusterman 1998; Hemilä et al. 2006; Mulsow et al. 2011; Reichmuth et al. 2013). In addition, to subdividing pinnipeds into their two families, the upper end of the hearing range for phocids has been extended based on data presented in Møhl 1968; Terhune and

[8] Functional hearing ranges are not meant to encompass the entire range of frequencies a functional hearing group is able to detect via mechanisms beyond the auditory system but rather represent the range of frequencies a group hears without incorporating non-acoustic mechanisms (Wartzok and Ketten 1999). For example, Au et al. 1997 reported hearing thresholds for Risso's dolphins and false killer whales exposed to ATOC signals (75 Hz), which were more than 60 to 70 dB above the region of best hearing. Thus, these signals were considered outside these species' functional hearing range.

[9] NOAA considered separating sperm whales from other MF cetaceans, not enough data are available to stipulate exactly how this should be done.

[10] Species included: Minke, fin, humpback, and North Atlantic right whales. Watkins et al. 1986 specifically indicated "Most whales reacted to sounds with frequencies from approximately 15 Hz to 28 kHz."

[11] NOAA is aware of preliminary data from Cranford (2014), whose recent simulations indicate that mysticetes may hear via both pressure-loaded and bone conduction mechanisms, with bone conduction being dominant. Additionally, these simulations were used to predict an audiogram for a fin whale calf.

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Ronald 1972; Ridgway and Joyce 1975; Hemilä et al. 2006, and Kastelein et al. 2009. The functional hearing range of otariids was based on data from Schusterman et al. 1972 and Kastak and Schusterman 1998.

- Addition of hourglass (*Lagenorhynchus cruciger*) and Peale's (*L. australis*) dolphins to high-frequency functional hearing group: Echolocation data (Kyhn et al. 2009; Kyhn et al. 2010; Tougaard and Kyhn. 2010) indicate that these two species produce sounds (i.e., higher mean peak frequency) similar to other narrow band high-frequency cetaceans, such as porpoises, *Kogia*, and *Cephalorhynchus*, and are distinctly different from other *Lagenorhynchus* species. Genetic data also suggest these two species are more closely related to *Cephalorhynchus* species (May-Collado and Agnarsson 2006). Thus, NOAA has decided to move these two species from the mid-frequency functional hearing group (MF cetaceans) to the high-frequency functional hearing group (HF cetaceans).

NOAA's modification results in marine mammal functional hearing groups being defined in this Guidance as depicted in Table 1.

Table 1: Marine mammal functional hearing groups.

Functional Hearing Group	Functional Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 25 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	200 Hz to 180 kHz
Phocid pinnipeds (underwater) (true seals)	75 Hz to 100 kHz
Otariid pinnipeds (underwater) (sea lions and fur seals)	100 Hz to 48 kHz

***** Represents frequency band of hearing for entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Functional hearing is defined as the range of frequencies a group hears without incorporating non-acoustic mechanisms (Wartzok and Ketten 1999). This is ~60 to ~70 dB above best hearing sensitivity (Southall et al. 2007) for all functional hearing groups except LF cetaceans, where no direct measurements on hearing are available. For LF cetaceans, the lower range is based on recommendations from Southall et al. 2007 and the upper range is based on information on inner ear anatomy and vocalizations.

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2.2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS

The ability to hear sounds varies across a species functional hearing range. Most mammal audiograms have a typical "U-shape", with frequencies at the bottom of the "U" being those to which the animal is more sensitive, in terms of hearing (i.e. the animal's best hearing range; for example audiogram, see Glossary, Figure E1). Auditory weighting functions best reflect an animal's ability to hear a sound (may not necessarily reflect how an animal will perceive that sound and behaviorally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted (e.g., A-weighting for humans where frequencies below 1 kHz and above 6 kHz are deemphasized based on the inverse of the idealized (smoothed) 40-phon equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz; e.g., Harris 1998). Other types of weighting functions exist for humans (e.g., B, C, D) that deemphasize different frequencies to different extremes (e.g., flattens equal-loudness perception across wider frequencies with increasing received level; for example, C-weighting is uniform from 50 Hz to 5 kHz; ANSI 2011).

Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS acoustic threshold levels expressed in the cumulative sound exposure level metric (SEL_{cum})[12], which take into account what is known about marine mammal hearing (Southall et al. 2007; Finneran and Jenkins 2012). The U.S. Navy, via a Navy Technical Report (Finneran 2015), recently developed updated marine mammal auditory weighting functions that reflect new data on:

- Marine mammal hearing (e.g., Ketten 2014; Ketten and Mountain 2014; Sills et al. 2014; Cranford and Krysl, 2015).

- Marine mammal equal latency contours (e.g., Reichmuth 2013; Wensveen et al. 2014; Mulsow et al. 2015).

- Effects of noise on marine mammal hearing (e.g., Kastelein et al. 2012a; Kastelein et al. 2012b; Finneran and Schlundt 2013; Kastelein et al. 2013a; Kastelein et al. 2013b; Popov et al. 2013; Kastelein et al. 2014b; Kastelein et al. 2014a; Popov et al. 2014; Finneran et al. 2015; Kastelein et al., 2015a; Kastelein et al. 2015b).

This recent update reflect a transition from auditory weighting functions that have previously been more similar to human dB(C) functions to those more similar to human dB(A) functions. Updated marine mammal auditory weighting functions also provide a more consistent approach/methodology for all functional hearing groups.

Upon evaluation, NOAA preliminarily determined that the Navy's proposed methodology (Finneran 2015) reflects the best available science and decided to incorporate the methodology directly into our Guidance. However, before doing so, NOAA had the Navy's

[12] Auditory weighting functions are not to be applied to PTS or TTS onset acoustic threshold levels expressed as the peak pressure metric (i.e., peak pressure thresholds are unweighted).

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methodology peer reviewed (see Appendix D for details on peer review and link to Peer Review Report).

2.2.1 Use of Auditory Weighting Functions in Assessing Susceptibility to Noise-Induced Hearing Loss

Auditory weighting functions are used for human noise standards to assess the overall hazard of noise on hearing. Specifically, the human auditory weighting function provides a "rating that indicates the injurious effects of noise on human hearing" (OSHA 2013). Thus, while these functions are based on regions of equal loudness and best hearing, in the context of human risk assessments, as well as their use in this document, they are meant to reflect the susceptibility of the ear to noise-induced threshold shifts. As described later in this document, the region of enhanced susceptibility to noise exposure may not perfectly mirror a species region of best hearing (e.g., TTS measurements from bottlenose dolphin, belugas, and Yangtze finless porpoise support this). Thus, within this document, auditory weighting functions are meant to assess risk of noise-induced hearing loss and do not necessarily encompass the entire range of best hearing (i.e., MF and HF auditory weighting functions) for every species within the functional hearing group.

2.2.2 Marine Mammal Auditory Weighting Functions

Updated frequency-dependent marine mammal auditory weighting functions were derived using data on hearing ability (composite audiograms), effects of noise on hearing, and data on equal latency (Finneran 2015). Separate functions were derived for each marine mammal functional hearing group (Figures 1 and 2).

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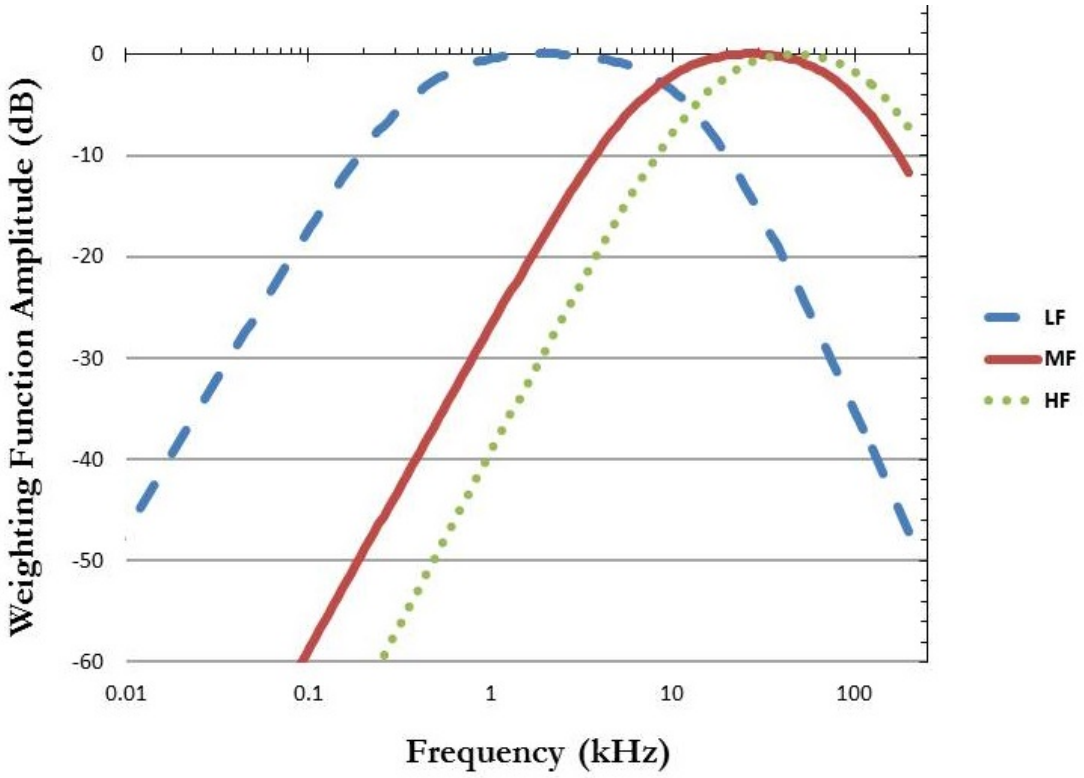


Figure 1: **Auditory weighting functions for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans.**

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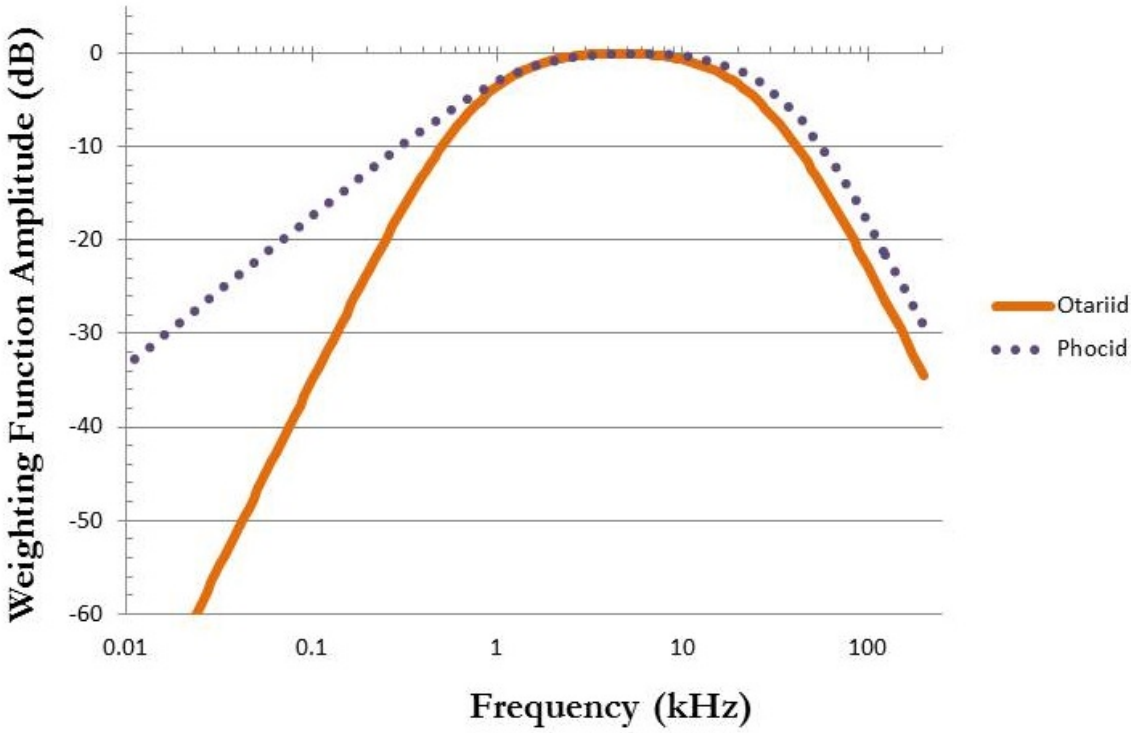


Figure 2: Underwater auditory weighting functions for otariid and phocid pinnipeds.

The overall shape of all auditory weighting functions is based on a generic band-pass filter described by Equation 1:

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\} \qquad \textbf{Equation 1}$$

where $W(f)$ is the weighting function amplitude in decibels (dB) at a particular frequency (f) in kilohertz (kHz). The function shape is determined by the following weighting function parameters:

- Low-frequency exponent (a): This parameter determines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As the frequency decreases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20a$ dB/decade.

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- High-frequency exponent (*b*): Rate at which the weighting function amplitude declines with frequency at the upper frequencies. As the frequency increases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20b$ dB/decade.

- Low-frequency cutoff (f_1): This parameter defines the lower limit of the band-pass filter (i.e., the lower frequency where weighting function amplitude begins to roll off or decline from the flat, central portion of the function). This parameter is directly dependent on the value of the low-frequency exponent (*a*).

- High-frequency cutoff (f_2): This parameter defines the upper limit the band-pass filter (i.e., the upper frequency where weighting function amplitude begins to roll off or decline from the flat, central portion of the function). This parameter is directly dependent on the value of the high-frequency exponent (*b*).

- Weighting function gain(*C*): This parameter determines the vertical position of the function and is adjusted to set the maximum amplitude of the weighting function to 0 dB.

Finneran (2015) illustrates the influence of each parameter value on the shape of the weighting function (Appendix A, Figure 2). Equation 1 is equivalent to weighting function presented in Finneran and Jenkins (2012), when the *a* and *b* parameters are both equal to two.

In association with auditory weighting functions are exposure functions that illustrate how auditory weighting functions relate to auditory threshold levels (i.e., have "U-shape" similar to audiograms). Exposure functions (Equation 2) are the inversion of Equation 1:

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$$

Equation 2

where $E(f)$ is the acoustic exposure as a function of frequency (f), K the gain parameter is a constant, which is adjusted to set the minimum value of the curve to the weighted PTS/TTS onset auditory threshold level, and all other parameters the same as those in Equation 1. Figure 3 illustrates how the various weighting parameters relate to one another in both the auditory weighting and exposure functions.

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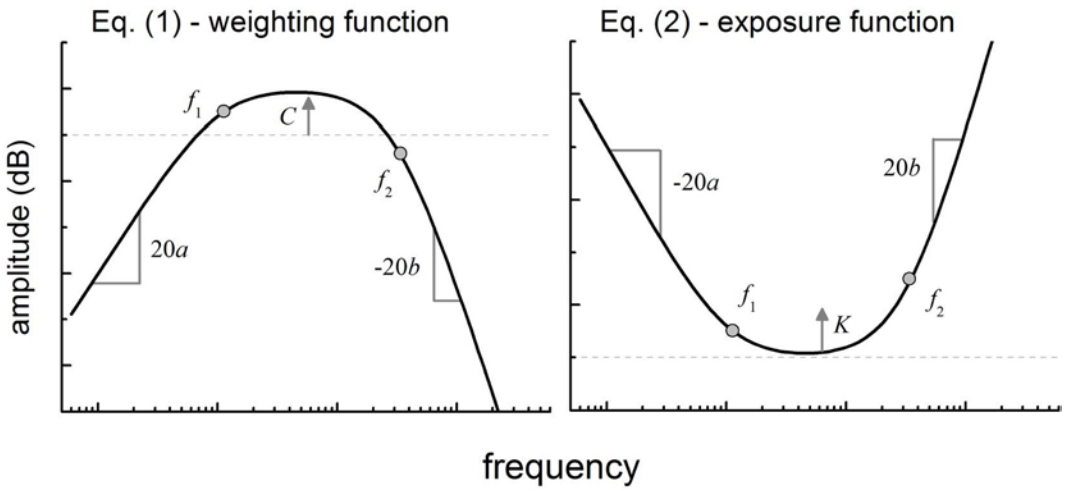


Figure 3: Illustration of function parameter in both auditory weighting functions and exposure functions (from Finneran 2015). Reference to Equations 1 and 2 match those in the Guidance.

Finneran (2015) (Appendix A, Figures E-2 and E-3) provides a comparison of these updated auditory weighting functions with previously derived weighting functions (Finneran and Jenkins 2012).

2.2.3 Derivation of Function Parameters

Numeric values associated with weighting function parameters were derived from available data from audiograms (measured and predicted), equal latency contours, and marine mammal TTS data using the following steps from Finneran (2015):

1. Derivation of marine mammal composite audiograms for each functional hearing group.
    a. This was completed by compiling available auditory threshold data for all individuals[13] within a functional hearing group (Table 2; See also Appendix A, Table 2 and Figures 5 and 6). Behavioral audiograms, opposed to those obtained by auditory evoked potentials (AEP), were used derive composite audiograms. This was because thresholds obtained using AEP data are usually elevated, especially at lower frequencies, compared to those obtained

[13] Data from an individual was only included once for a particular frequency. If there were multiple data points at a particular frequency for an individual, thresholds were averaged. Individuals with known high-frequency hearing loss or those with aberrant audiograms were not included in the analysis.

1 **Table 2: Summary of data available for deriving composite audiograms.†**
2

Functional Hearing Group	Species (number of individuals)	References
Low-frequency (LF) cetaceans*	Blue whale (3)	Ketten 2014
	Fin whale (1)	Cranford and Krysl 2015
	Humpback whale (6)‡	Ketten and Mountain 2014
	Minke whale (3)	Ketten and Mountain 2011; Ketten 2014
Mid-Frequency (MF) cetaceans	Beluga (9)	White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989; Ridgway et al. 2001; Finneran et al. 2005b
	Bottlenose dolphin (6)	Johnson 1967; Ljungblad et al. 1982; Lemonds 1999; Brill et al. 2001; Schlundt et al. 2008; Finneran et al. 2010a
	False killer whale (1)	Thomas et al. 1988
	Killer whale (2)	Szymanski et al. 1999
	Risso's dolphin (1)	Nachtigall et al. 1995
	Pacific white-sided dolphin (1)	Tremel et al. 1996
	Striped dolphin (1)	Kastelein et al. 2003
	Tucuxi (1)	Sauerland and Dehnhardt 1998
High-frequency (HF) cetaceans	Amazon River dolphin (1)	Jacobs and Hall 1972
	Harbor porpoise (2)	Kastelein et al. 2002b; Kastelein et al. 2010
Phocid pinnipeds (underwater)	Caspian seal (1)	Babushina 1997
	Harbor seal (5)	Møhl 1968; Terhune 1988; Kastelein et al. 2009b; Reichmuth et al. 2013
	Harp seal (1)	Terhune and Ronald 1972
	Northern elephant seal (1)	Kastak and Schusterman 1999
	Ringed seal (2)	Terhune and Ronald 1975
	Spotted seal (2)	Sills et al. 2014
Otariid pinnipeds^ (underwater)	California sea lion (4)	Mulsow et al. 2012; Reichmuth and Southall 2012; Reichmuth et al. 2013
	Northern fur seal (3)	Moore and Schusterman 1987; Babushina et al. 1991
	Steller sea lion (2)	Kastelein et al. 2005

† More details on individual subjects are available in Appendix A (Table 2)

* All LF cetacean data are from predicted mathematical models, since direct measurements of hearing are not available. Number of individuals in next column represents the number of specimens/samples used to derive predicted audiograms.

‡ Ketten and Mountain (2014) incorporates specimens/samples used by Houser et al. (2001) as well as additional specimens. This the reason Houser et al. (2001) was not directly used.

^ The otariid pinniped (underwater) functional hearing group's composite audiogram contains data from a single Pacific walrus (*Odebenus rosmarus*) from Kastelein et al. 2002a and a single sea otter (*Enhydra lutris nereis*)

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from Ghoul and Reichmuth 2014. For frequencies below 30 kHz, the difference in the composite audiogram with and without these data are < 2 dB. For comparison, see Appendix A, Figure 4.

behaviorally (i.e., behavioral audiograms were determined to be more representative of hearing ability compared to those obtained by AEP).

For the LF cetacean group, where direct measurements of hearing are not available, predicted audiograms, based on mathematical models (Ketten 2014; Ketten and Mountain 2014; Cranford and Krysl 2015), were used (Table 2).

b. Linear interpolation was completed to estimate thresholds at each unique frequency present in any of the data sets such that no data were excluded.

c. Composite audiograms were derived using original data and then thresholds were normalized by subtracting the lowest threshold value[14] for the individual.

d. The median (50th percentile) threshold was calculated for each frequency and fit by nonlinear regression via the following function (Equation 3), which provides at lower frequencies linear-log roll off with variable slope at high frequencies a steep rise:

$$T(f) = T_0 + A\log_{10}\left(1+\frac{F_1}{f}\right)+\left(\frac{f}{F_2}\right)^B$$

Equation 3

Within Equation 3, f, T_0, F_1, F_2, A, and B are all fitting parameters with the following values (Table 3; Figure 4):

[14] Since direct measurements of hearing are not available for LF cetaceans the lowest auditory threshold for this functional hearing group had to be estimated at 65 dB (Wenz 1962; Clark and Ellison 2004).

Table 3: Best-fit parameters for Equation 3 for normalized data*.

Functional Hearing Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
Low-frequency (LF) cetaceans	-2.67	0.594	3.11	35.9	1.84	0.992
Mid-frequency (MF) cetaceans	3.06	14	65.7	31.4	4.87	0.971
High-frequency (HF) cetaceans	0.258	21.8	132	36.1	21.0	0.959
Phocid pinnipeds (underwater)	-46.6	4820	3.69	16.4	1.38	0.941
Otariid pinnipeds (underwater)	2.39	0.364	13.3	73.7	3.55	0.955

* Best-fit parameters for original data are provided in Appendix A, Table 3.

R^2 indicates goodness of fit values.

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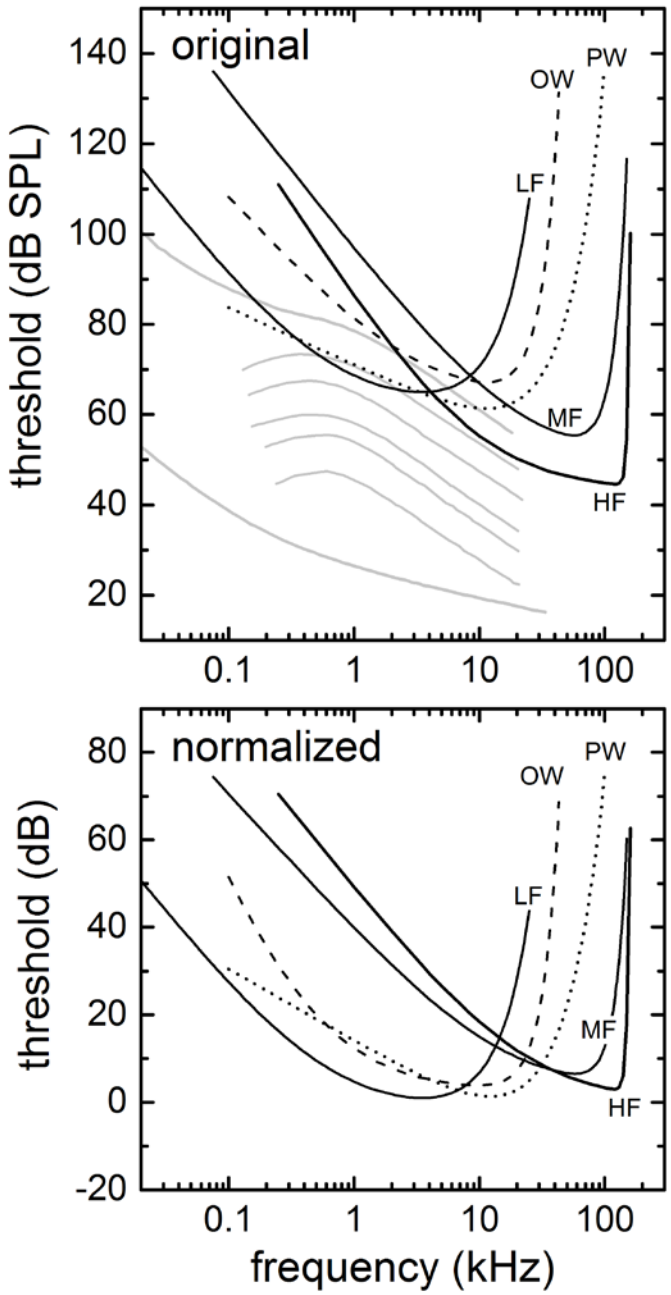


Figure 4: **Resulting composite audiograms derived using original data (top) and normalized data (bottom) for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans and phocid (PW) and otariid (OW) pinnipeds (from Finneran 2015). For LF cetaceans, data were normalized by setting the lowest threshold to 65 dB based on Clark and Ellison (2004). The gray lines in the upper panel represent ambient noise spectral density levels from Wenz (1962).**

e. From the composite audiogram, the frequency of lowest threshold and slope at the lowest frequencies were calculated. Slopes were calculated across of a frequency range of one decade beginning with the lowest frequency present for each functional hearing group (Table 4).

Table 4: Frequency of best hearing (f_0) from normalized data and magnitude of the low-frequency slope (s_0).

Functional Hearing Group	Composite Audiogram Data		Equal Latency Curves‡
	f_0 (kHz)	s_{0*} (dB/decade)	s_0 (dB/decade)
Low-frequency (LF) cetaceans	3.5	32 (30†)	N/A
Mid-frequency (MF) cetaceans	58	31	31
High-frequency (HF) cetaceans	120	34	50
Phocid pinnipeds (underwater)	13	16	N/A
Otariid pinnipeds (underwater)	10	39	N/A

* Smallest low-frequency slope used, which results in composite audiogram data always being used over equal latency curves.

‡ Equal latency data are available for bottlenose dolphins (Mulsow et al. 2015) and harbor porpoise (Wensveen et al. 2014) (See Appendix A, Figure 8).

† For LF cetaceans, Finneran (2015) decided it was more appropriate to base the slope on those associated with low-frequency ambient noise curves (Wenz 1962) of 30 dB/decade, rather than the predicted audiogram slope of 32 dB/decade.

2. The low-frequency exponent (a) was defined using the smaller of the low-frequency slope from the composite audiogram or the lower-frequency slope of the equal latency contours (Table 4) and then divided by twenty ($s_0/20$; Table 5). This results in the slope matching the shallower slope of the audiogram.

Table 5: Derivation of low-frequency exponent (a).

Functional Hearing Group	s_0 (dB/decade)	a*
Low-frequency (LF) cetaceans	30	1.5
Mid-frequency (MF) cetaceans	31	1.6
High-frequency (HF) cetaceans	34	1.7
Phocid pinnipeds (underwater)	16	0.8
Otariid pinnipeds (underwater)	39	2

* $a = s_0/20$

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The exception to this procedure was for LF cetaceans, where Finneran (2015) determined it was more appropriate to use the slope associated with low-frequency ambient noise curves (i.e., 30 dB/decade; Wenz 1962), compared to those based on the predicted audiograms (i.e., 32 dB/decade).

3. The high-frequency exponent (b) was set equal to two to match previously derived marine mammal auditory weighting functions from Finneran and Jenkins (2012), since no new TTS are available at higher frequencies and equal latency data at these frequencies are considered highly variable.

4. Low- (f_1) and high-frequency cutoffs (f_2) were defined as the frequencies below and above the frequency of best hearing (f_0) from original data (Figure 4), where the threshold values were ΔT above the threshold at f_0 (Figure 5).

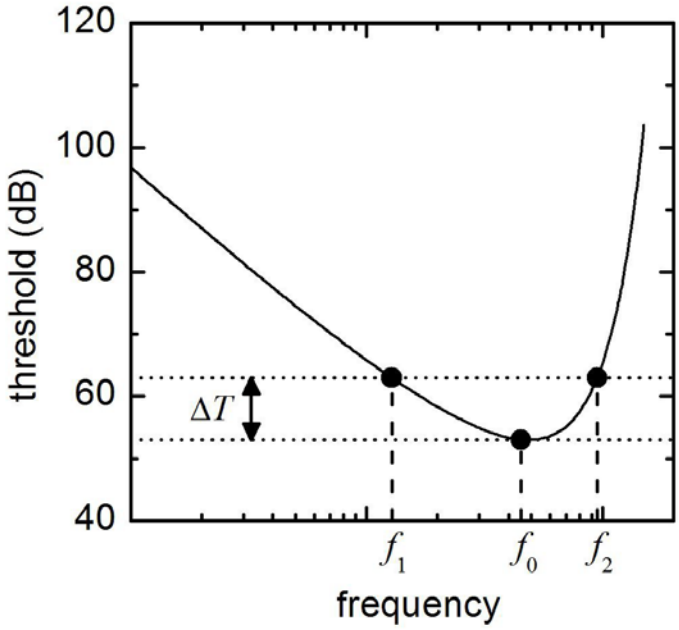


Figure 5: Low- and high-frequency cutoffs (from Finneran 2015).

To determine ΔT, the exposure function amplitude was calculated for MF and HF cetaceans examining ΔT values ranging from zero to 20 dB. Then K was adjusted to minimize the mean-squared error between the function amplitude and MF and HF cetacean TTS data (original and normalized) from non-impulsive, continuous exposures[15] (100% duty cycle; 12 data points) (Figure 6). The value of ΔT resulting the lowest mean-squared error was eleven for both the normalized and original data (For illustration, see Appendix A, Figure 16). This value was used for other

[15] There were not enough TTS data available for other functional hearing groups to perform this step.

functional hearing groups. Resulting low- (f_1) and high-frequency cutoffs (f_2) are summarized in Table 7.

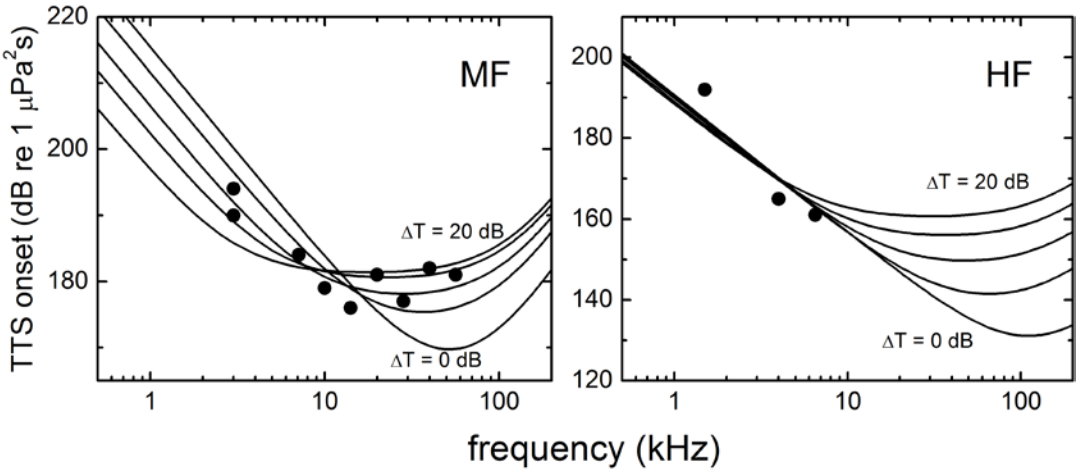


Figure 6: Illustration of ΔT adjustment from 0 to 20 dB on TTS exposure function for MF (left) and HF (right) cetaceans (from Finneran 2015).

5. Functional hearing groups where TTS data are available (i.e., MF and HF cetaceans and phocid and otariid pinniped) were used to define K (Step 4 above). For LF cetaceans, where data were not available, K was estimated by assuming the numeric difference between auditory threshold (Figure 4, original data) and TTS onset at f_0 (See Section 2.3.4 for summary and Appendix A for specific details) at the frequency of best hearing would be similar across functional hearing groups (Table 6).

Table 6: Procedure used to estimate TTS onset values for low-frequency cetaceans, where no data exist.

Functional Hearing Group	f_0 (kHz) Original data	Auditory threshold at f_0	TTS onset at f_0 (SEL_{cum})	Difference
Low-frequency (LF) cetaceans	3.5	65 dB*	188 dB (estimated)	123*
Mid-frequency (MF) cetaceans	58	55 dB	180 dB	125
High-frequency (HF) cetaceans	120	45 dB	153 dB	108
Phocid pinnipeds (underwater)	11	61 dB	182 dB	121
Otariid pinnipeds (underwater)	12	67 dB	200 dB	133

* For LF cetaceans, the threshold value at frequency of best hearing was estimated based on range of 60-70 dB provided by Clark and Ellison (2004). The difference between lowest threshold value and TTS onset value was estimated by using the median values of the differences for the other functional hearing groups.

6. The weighting function (C) was determined by substituting parameters a, b, f_1, and f_2 in Equation 1 and setting the peak amplitude of the function to zero.

The resulting numeric values associated with these parameters for each functional hearing group functions, as proposed in Finneran (2015), are listed in Table 7 and resulting in Figures 1 and 2.

Table 7: Summary of weighting function parameters.

Functional Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)
Low-frequency (LF) cetaceans	1.5	2	0.38	13	0.43	187
Mid-frequency (MF) cetaceans	1.6	2	7.4	110	1.02	178
High-frequency (HF) cetaceans	1.7	2	16	150	1.63	149
Phocid pinnipeds (underwater)	0.8	2	1.3	37	0.38	181
Otariid pinnipeds (underwater)	2.0	2	0.77	27	0.49	198
Note: a and b are dimensionless parameters						

Note: Appendix A, Figure 17 illustrates that the resulting exposure function and subsequent weighting function is wider than the composite audiogram (i.e., this methodology results in an auditory weighting function that is broader than a simple inverse audiogram, which has been recommended to assess impacts; e.g., Tougaard et al. 2015).

2.2.3.1 Generalized Auditory Weighting Function for Low-Frequency Cetaceans

Finneran (2015) also proposed an updated auditory weighting function for LF cetaceans based on similar methodology used to create auditory weighting functions for other marine mammal species (Figure 1). Since direct measurements of hearing are not available for any species within this functional hearing group, predicted audiograms for blue (Ketten 2014), fin (Cranford and Krysl 2015, minke (Ketten and Mountain 2011; Ketten 2014), and humpback (Ketten and Mountain 2014) whales were used to derive weighting functions.

NOAA acknowledges that, as more data become available, marine mammal hearing ranges may require future modification and that it may be necessary to divide LF cetaceans into subdivisions. However, at this time, NOAA does not believe there are enough data to support further LF cetacean divisions and subsequent auditory weighting functions, especially since no direct information on hearing is available for this group.

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2.2.4 Application of Marine Mammal Auditory Weighting Functions for PTS Onset Acoustic Threshold Levels

The application of marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of overlapping with biologically important frequencies (e.g., frequencies used for environmental awareness, communication or the detection of predators or prey), and not only the frequencies of interest or concern for the completion of the sound-producing activity (i.e., context of sound source). Marine mammal auditory weighting functions are considered in two aspects of a effects analysis in terms of acoustic threshold levels:

1) Data evaluation: After considering and evaluating all available data, establishing numerical acoustic threshold levels for PTS onset (for SEL_{cum} metric threshold only; the peak pressure metric threshold is not weighted), which is NOAA's responsibility.

2) Implementation: Determining isopleths associated with onset PTS threshold levels (i.e., modeling of the area impacted around a source) associated with an activity, which is typically completed by an action proponent/federal agency.

If the frequencies produced by a sound source are outside the range of a functional hearing group's most susceptible hearing range (where the weighting function amplitude is 0), sounds must have a higher sound pressure level to produce a similar threshold shifts (i.e., PTS onset) to those in the most susceptible hearing range. Because auditory weighting functions take a functional hearing group's differing susceptibility to frequencies into account, the implementation of these functions typically results in smaller isopleths for frequencies where the group is less susceptible. Additionally, if the sound source produces frequencies completely outside the hearing range of a given functional hearing group (i.e., has no side bands that are capable of producing sound within the hearing range of a functional hearing group), then the likelihood of the sound causing noise-induced hearing loss is considered low[16].

Marine mammal auditory weighting functions should be used in conjunction with corresponding PTS onset acoustic threshold levels. If the use of the full auditory weighting function is not possible by an action proponent, NOAA has provided alternative PTS onset acoustic threshold levels to be used based on a simpler weighting function (See Appendix E).

Tougaard et al. (2014) review the impacts of using auditory weighting functions and various considerations when applying these during the data evaluation and implementation stages (e.g., consequences of using too broad or too narrow of a filter) and suggest some modifications (correction factors) to account for these considerations. However, NOAA believes it would be difficult to establish a "correction factor" as suggested, since there are

[16] The potential for sound to damage beyond the level the ear can perceive exists (Akay 1978), which is why the acoustic thresholds levels also include the peak sound pressure level metric.

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no data to support doing so. Additionally, the means by which NOAA is applying auditory weighting functions is supported and consistent with what has been done for humans (i.e., A-weighted thresholds used in conjunction with A-weighting during implementation).

2.2.4.1 Maintaining Full Spectrum for Future Analysis

The application of marine mammal auditory weighting functions should completed after sound field measurements have been obtained (i.e., post-processing; auditory weighting functions should not be applied beforehand), with the total spectrum of sound preserved for later analysis (i.e., if weighting functions are updated or if there is interest in additional species data can still be used). Furthermore, the peak pressure acoustic threshold levels are unweighted.

2.3 PTS Onset Acoustic Threshold Levels

This section provides numeric acoustic threshold levels for the onset of PTS (Tables 8). Dual metrics of SEL_{cum} and peak sound pressure level have been recommended as most appropriate for establishing PTS onset acoustic threshold levels for marine mammals (Southall et al. 2007; Finneran 2015).

Table 8: Summary of PTS onset dual metric acoustic threshold levels*.

	PTS Onset Threshold Levels (Received Level)	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* 230 dB_{peak} **&** 192 dB SEL_{cum}	*Cell 2* 230 dB_{peak} **&** 207 dB SEL_{cum}
Mid-Frequency (MF) Cetaceans	*Cell 3* 230 dB_{peak} **&** 187 dB SEL_{cum}	*Cell 4* 230 dB_{peak} **&** 199 dB SEL_{cum}
High-Frequency (HF) Cetaceans	*Cell 5* 202 dB_{peak} **&** 154 dB SEL_{cum}	*Cell 6* 202 dB_{peak} **&** 171 dB SEL_{cum}
Phocid Pinnipeds (Underwater)	*Cell 7* 230 dB_{peak} **&** 186 dB SEL_{cum}	*Cell 8* 230 dB_{peak} **&** 201 dB SEL_{cum}
Otariid Pinnipeds (Underwater)	*Cell 9* 230 dB_{peak} **&** 203 dB SEL_{cum}	*Cell 10* 230 dB_{peak} **&** 218 dB SEL_{cum}

* Dual metric acoustic threshold levels: Use whichever level [dB_{peak} or dB SEL_{cum}] exceeded first. All SEL_{cum} acoustic threshold levels (re: 1 μPa^2-s) incorporate marine mammal auditory weighting functions, while peak pressure thresholds should not be weighted. Note: Acoustic threshold levels for impulsive or non-impulsive sources are based on temporal characteristics at the source and not the receiver.

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The SEL_{cum} could be exceeded in multitude of ways (i.e., varying exposure levels and durations, duty cycle). It is valuable for action proponents, if possible, to indicate under what conditions these acoustic threshold levels will be exceeded.

Note: In this Table, dB_{peak}, is equivalent to the ANSI abbreviation of L_{pk} and SEL_{cum} is equivalent to the ANSI abbreviation of L_E (ANSI 2013).

Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958; Ward et al. 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008). Southall et al. (2007) also recommended this definition of PTS onset.

As mentioned earlier, PTS onset acoustic threshold levels for marine mammals has not been directly measured and must be extrapolated from available TTS onset measurements and associated threshold levels. Thus, based on cetacean measurements from TTS studies (see Southall et al. 2007 and Finneran 2015 for a review and Table 10, a threshold shift of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation[17] in a subject's normal hearing ability and is typically the minimum amount of threshold shift that can be differentiated in most experimental conditions (Finneran et al. 2000; Schlundt et al. 2000; Finneran et al. 2002). Thus, NOAA has set the onset of TTS at the lowest level that exceeds recorded variation (i.e., 6 dB).

There are different mechanisms associated (e.g., anatomical, neurophysiological) with TTS vs. PTS onset making the relationship between these types of threshold shifts not completely direct. Nevertheless, the only data available for marine mammals currently and likely in the future will be from TTS studies (i.e., unlike for terrestrial mammal where direct measurements of PTS exist). Thus, TTS represents the best information available for which PTS can be estimated.

The acoustic threshold levels presented in Table 8 replace all previously issued NOAA acoustic threshold levels for PTS onset. The acoustic threshold levels consist of both an acoustic threshold level and weighting function for the SEL_{cum} metric (weighting functions are considered not appropriate for peak pressure metric).

NOAA recognizes that the implementation of marine mammal weighting functions represents a new factor for consideration, which may extend beyond the capabilities of some action proponents. Thus, NOAA has developed alternative acoustic threshold levels for those who cannot fully apply weighting functions associated with the SEL_{cum} metric (See Appendix E).

[17] Similarly, for humans, NIOSH (1998) regards the range of audiometric testing variability to be approximately 5 dB.

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2.3.1 Impulsive and Non-Impulsive Acoustic Threshold Levels

Within the Guidance, sources are divided into impulsive and non-impulsive based on physical characteristics at the source, with impulsive sound having physical characteristics that make them more injurious[18] (e.g., high peak pressures and rapid rise times) than non-impulsive sound sources (terrestrial mammal data: Buck et al. 1984; Dunn et al. 1991; Hamernik et al. 1993; Clifford and Rogers 2009; marine mammal data: reviewed in Southall et al. 2007 and Finneran 2015). NOAA acknowledges that the characteristics of the sound at the receiver are what are considered in our analyses for determining potential impacts. However, understanding these physical characteristics in a dynamic system with receivers moving over space and time is difficult. Nevertheless, it is known that as sound propagates from the source the characteristics of impulsive sounds that make them more injurious start to dissipate due effects of propagation (e.g., time dispersion/time spreading; Urick 1983; Sertlek et al. 2014).

As Southall et al. (2007) stated "…certain sound sources (e.g., seismic airguns and pile driving) may produce pulses at the source but, through various propagation effects, may meet the nonpulse definition at greater distances (e.g., Greene & Richardson, 1988). This means that a given sound source might be subject to different exposure criteria, depending on the distance to the receiver and intervening propagation variables. While this is certainly realistic for many real-world exposures, measurements at the animal are often not practical. Changes in sound characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance because sharp transient peaks become less prominent."

Because of this, the Guidance, for assessing the impacts on hearing[19], divides and defines sources as the following:

- Impulsive: produce sounds that are transient, brief (less than 1 second), broadband, and typically consist of high peak pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005).

- Non-impulsive: produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak pressure with rapid rise time that impulsive sounds do (ANSI 1995; NIOSH 1998).

[18] Exposure to impulsive sounds more often lead to mechanical damage of the inner ear, as well as more complex patterns of hearing recovery (e.g., Henderson and Hamernik 1986; Hamernik and Hsueh 1991).

[19] Note: The definition of impulsive in this document relates specifically to noise-induced hearing loss and specifies the physical characteristics of an impulsive sound source, which likely gives them a higher potential to cause auditory injury. This definition captures how these sound types may be more likely to affect auditory physiology. However, these definitions are not meant to reflect how sounds have previously been characterized for "take" associated with behavioral harassment under NOAA's 120 dB (continuous) and 160 dB (impulse) MMPA thresholds.

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The characteristics that make impulsive sounds particularly injurious are their high peak pressures and rapid rise times (e.g., Ketten 1995; Richardson et al. 1995). Thus, it is necessary for NOAA to provide some quantitative means to determine when impulsive sounds are less likely to possess those physical characteristics that most likely result in auditory injury.

Within the Guidance, underwater high explosives, seismic airguns, and impact pile driving are the primary sources that comply with the physical characteristics of the definition of impulsive sounds. At close ranges, the sounds associated with these sources typically have primary[20] pulse durations of 0.05 s (50 ms) or less, with considerably short duration rise times (e.g., overview: Hildebrand 2009; explosives: Urick 1983 and Richardson et al. 1995; seismic: Wardle et al. 2001, Madsen et al. 2006, and Breitzke et al. 2008; impact pile driving: Caltrans 2012)[21].

2.3.1.1 Recommended Transition from Impulsive to Non-Impulsive Acoustic Threshold Levels Based on Peak Pressure to Pulse Duration Ratio

As primary pulses propagate through the environment, their physical characteristics begin to change, making them less likely to result in auditory injury (e.g., longer pulse length, decreased peak pressure; e.g., Richardson et al. 1995). The distance from the source where this transition occurs depends on a multitude of factors (e.g., source characteristics, including frequency, bathymetry, water depth, bottom sediment composition). However, based on previously collected measurements at various distances to a particular source, as well as marine mammal TTS data from exposure to impulsive sounds (more detail is provide in Appendix B), some general approximations can be made. In this regards, NOAA has approximated that 3 km conservatively estimates the range from a source where most impulsive sounds transition to having less injurious characteristics.

Application of Transition Range

If exposure modeling predicts that an impulsive sound produces PTS onset less than 3 km from the source, the action proponent must use the predictions from this range.

If, however, exposure modeling predicts that an impulsive sound produces a PTS onset isopleth, greater than 3 km from the source, then the action proponent may wish to explore substituting the non-impulsive PTS onset acoustic threshold level for the impulsive acoustic

[20] Primary pulses or first arrivals are those components independent of interacting with properties of the sea floor and/or subsurface and independent of bubble energy (Breitzke et al. 2008). The duration of the primary pulse consists of the time between 5% and 95% of a pulse's total cumulative energy (Madsen 2005).

[21] Cudahy and Parvin 2001 (Figure 2-2) provide a comparison of primary pulses, in terms of peak pressure and pulse duration, between explosives and seismic airguns. In general, high explosive blasts have higher peak pressures and faster rise times compared to seismic airgun shots and impact pile driving strikes.

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threshold level to calculate the isopleth where auditory injury would occur for that functional hearing group (Note: the action proponent is not obligated to use this option). If the proponent chooses to do this, they should do so in the following manner:

- *If upon substitution*, the non-impulsive PTS onset acoustic threshold level results in a predicted auditory injury isopleth less than 3 km, then the action proponent must still calculate PTS onset out to the 3 km transition range.

- *If upon substitution*, the non-impulsive PTS onset acoustic threshold level results in a predicted auditory injury isopleth greater than 3 km, then the action proponent may calculate PTS onset based on this new isopleth rather than the previous isopleth predicted using the impulsive PTS onset acoustic threshold level.

If this substitution is made, it needs to be clearly stated by the action proponent in their application. Further discussion about the appropriateness of this adjustment with NOAA may be necessary to ensure that the adjustments best reflect the particular activity and/or expected impacts to marine mammals in the area.

NOAA acknowledges that based on available data (Appendix B, Table B1), a 3-km transition range may not be appropriate for sounds such as high explosives, due to their extremely short pulse durations and high peak pressures[22] relative to other impulsive sources (i.e., alternative means of examining transition range, such as decay time constants, specifically associated with explosives, may be more appropriate; e.g., Soloway and Dahl 2014).

Note: This proposed methodology does not suggest that PTS onset, as result of exposure to impulsive or non-impulsive sounds, beyond 3 km is entirely unlikely, especially based on the potential for long exposure durations or for situations where acoustic threshold levels are low), but instead recognizes that beyond a certain distance impulsive sounds begin to lose those physical characteristics making them most injurious.

2.3.2 Qualitative Factors for Consideration

In addition to received level, NOAA recognizes that other factors, such as frequency and duration of exposure, are also important to consider within the context of PTS onset acoustic threshold levels. Thus, in addition to numerical acoustic threshold levels based on level, NOAA has provided qualitative factors that it recommends are considered within the comprehensive effects analysis. They are presented as general trends associated with noise-

[22] Note: There are additional non-auditory acoustic threshold levels for high explosives (i.e., lung and gastrointestinal tract injury), as well as a peak pressure PTS onset acoustic threshold level (part of this Guidance's dual acoustic threshold levels). Action proponents should evaluate all non-auditory and auditory injury acoustic threshold levels and use the one that produces the largest isopleth when assessing potential impacts. For underwater high explosives, it is not expected that the most conservative isopleth will result from the PTS acoustic threshold level expressed in the SEL_{cum} metric (i.e., PTS onset acoustic threshold level expressed as peak pressure or non-auditory acoustic threshold levels are predicted to result in the largest, most conservative isopleths).

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induced hearing loss observed from the limited number marine mammal TTS measurement studies and further supported by human and terrestrial mammal research (Table 9).

Table 9: Qualitative factors for consideration (frequency and duration of exposure) in association with PTS onset acoustic threshold levels.

I. Frequency*: General Trend Identified: 1) Growth of threshold shifts (TS): Growth rates of TS (dB of TTS/dB noise) are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran and Schlundt 2013)
II. Duration: General Trends Identified: 1) Violation of Equal Energy Hypothesis (EEH): Non-impulsive, intermittent exposures require higher SEL_{cum} to induce a TS compared to continuous exposures of the same duration (Mooney et al. 2009a; Finneran et al. 2010b; Kastelein et al. 2014a) 2) Violation of EEH: Exposures of longer duration and lower levels induce a TTS at a lower level than those exposures of higher level (below the critical level) and shorter duration with the same SEL_{cum} (Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a) 3) Recovery from a TS: With the same SEL_{cum}, longer exposures require longer durations to recover (Mooney et al. 2009b; Finneran et al. 2010a) 4) Recovery from a TS: Intermittent exposures recover faster compared to continuous exposures of the same duration (Finneran et al. 2010b; Kastelein et al. 2014a)
III. Cumulative Exposure: General Trend Identified: 1) Animals may be exposed to multiple sound sources and stressors, beyond acoustics, during an activity, with the possibility of the possibility of additive or synergistic effects (e.g., Sih et al. 2004; Rohr et al. 2006)
* Frequency-dependent hearing loss and overall hearing ability within a functional hearing group is taken into account, quantitatively, with auditory weighting functions.

Notes: These factors are provided only for qualitative consideration (i.e., there is not enough data to establish numerical acoustic threshold levels based on these added factors). Their intent is not to be used to reduce quantitatively predicted exposures produced by acoustic threshold levels. When more data become available, it may be possible to incorporate these factors into quantitative assessments.

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2.3.3 Metrics

2.3.3.1 Cumulative Sound Exposure Level (SEL_{cum}) Metric[23]

The SEL metric takes into account both received level and duration of exposure (ANSI 2013), both factors that contribute to noise-induced hearing loss. Often this metric is normalized to a single sound exposure of one second. NOAA intends for the SEL metric to account for the *accumulated* exposure (i.e., SEL_{cum} cumulative exposure over the duration of the activity within a 24-h period).

The recommended application of the SEL_{cum} metric is for individual activities/sources. It is not intended for accumulating sound exposure from multiple activities occurring within the same area or over the same time or to estimate the impacts of those exposures to an animal occurring over various spatial or temporal scales. Current data available for deriving acoustic threshold levels using this metric are based on exposure to only a single source and may not be appropriate for situations where exposure to multiple sources is occurring. As more data become available, the use of this metric can be re-evaluated, in terms of appropriateness, for application of exposure from multiple activities occurring in space and time.

Equal Energy Hypothesis

One assumption made when using the SEL_{cum} metric is the equal energy hypothesis (EEH), where it is assumed that sounds of equal SEL_{cum} produce the equal risk for hearing loss (i.e., if the SEL_{cum} of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks to a shorter duration exposure from a higher level source). As has been shown to be the case with humans and terrestrial mammals (Henderson et al. 1991), the EEH does not always accurately describe all exposure situations for marine mammals due the inherent complexity of predicting threshold shifts (e.g., Kastak et al. 2007; Mooney et al. 2009a; Mooney et al. 2009b; Finneran et al. 2010a; Finneran et al. 2010b; Finneran and Schlundt 2010; Kastelein et al. 2012b; Kastelein et al. 2013b; Kastelein et al. 2014a; Popov et al. 2014). Factors like level (e.g., overall level, sensation level, or level above background), duration, repetition rate (intermittent versus continuous exposure; potential recovery between intermittent periods), number of transient components (short duration and high amplitude), and/or frequency (especially in relation to hearing sensitivity) often are also important factors associated with threshold shifts (e.g., Buck et al. 1984; Clark et al. 1987; Ward 1991; Lataye and Campo 1996). This is especially the case for exposure to impulsive sound sources (Danielson et al. 1991; Henderson et al. 1991; Hamernik et al. 2003), which is why acoustic threshold levels are also expressed as a peak pressure metric (see next section). However, in many cases the EEH approach functions reasonably well as a first-order approximation, especially for higher-level, short-duration sound exposures such

[23] In this document, this metric is abbreviated SEL_{cum}, which is equivalent to the ANSI abbreviation of L_E (ANSI 2013).

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as those that are most likely to result in a TTS in marine mammals[24]. Additionally, no currently supported alternative method to accumulate exposure is available. If alternative methods become available, they can be evaluated when the Guidance is updated.

Recommended Accumulation Period

To apply the cumulative sound exposure level metric, accumulation time must be specified. Generally, it is predicted that most receivers will minimize the amount of time they remain in the closest ranges to a sound source/activity. Exposures at the closest point of approach are the primary exposures contributing to a receivers accumulated level (Gedamke et al. 2011). Additionally, several important factors determine the likelihood and duration of time a receiver is expected to be in close proximity to a sound source (i.e., overlap in space and time between the source and receiver). For example, accumulation time for fast moving (relative to the receiver), mobile sources, is driven primarily by the characteristics of source (i.e., speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and whether transient or resident to the area where the activity is occurring). NOAA recommends a baseline accumulation period of 24 hours, but acknowledges that there may be specific exposure situations where this accumulation period requires adjustment (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations).

Previous NOAA acoustic threshold levels have only accounted for proximity of the sound source to the receiver, but acoustic threshold levels in this Guidance (i.e., expressed as SEL_{cum}) now take into account the duration, as well as level of exposure. NOAA recognizes that accounting for duration of exposure, although supported by the best available science, adds a new factor, as far as application of this metric to real-world activities and that not all action proponents may have the ability to easily apply this additional component.

NOAA does not provide specifications necessary to perform exposure modeling and relies on the action proponent to determine the model that best represents their activity. However, NOAA acknowledges that different action proponents may have different capabilities and levels of modeling sophistication. NOAA has provided those applicants unable to apply various factors into their model with a simple means of approximating exposure (See Appendix E).

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[24] It is valuable for action proponents, if possible, to indicate under what conditions these acoustic threshold levels are likely to be exceeded.

2.3.3.2 Peak Pressure (dB_{peak}) Metric[25]

Sound exposure containing transient components (e.g., short duration and high amplitude; impulsive sounds) can create a greater risk of causing direct mechanical fatigue (as opposed to strictly metabolic) to the inner ear compared to sounds that are strictly non-impulsive (Henderson and Hamernik 1986; Levine et al. 1998; Henderson et al. 2008). Often the risk of damage from these transients does not depend on the duration of exposure (e.g., concept of "critical level," where damage switches from being primarily metabolic to more mechanical; short duration of impulse can be less than the ear's integration time, leading to the potential to damage beyond the level the ear can perceive (Akay 1978)). Human noise standards recognize and some provide separate acoustic threshold levels for impulsive sound sources in this metric (Occupational Safety and Health Administration (OSHA) 29 CFR 1910.95; Starck et al. 2003). Thus, SEL_{cum} is not an appropriate metric to capture these effects (i.e., often violates EEH; NIOSH 1998), which is why instantaneous peak sound pressure level has also been chosen as part of NOAA's dual metric acoustic threshold levels. Auditory weighting is not considered appropriate for use with this metric, as direct mechanical damage associated with sounds having high peak pressures typically does not strictly reflect the frequencies an individual species hears best (Ward 1962; Saunders et al. 1985; ANSI 1986; DOD 2004; OSHA 29 CFR 1910.95).

2.3.3.3 Comparison Among Metrics

NOAA's previous acoustic threshold levels were expressed as root-mean-square (dB_{rms}), which used a different metric from peak sound pressure levels (dB_{peak}) and SEL_{cum} that are being recommended for the PTS onset acoustic threshold levels in this Guidance. Thus, NOAA recommends caution when comparing prior acoustic threshold levels to the threshold levels presented in this document because they are based on different metrics (i.e., they are not directly comparable). For example, a 180 dB_{rms} level is not equal to a180 dB_{peak} level. Furthermore, the SEL_{cum} metric incorporates exposure duration and is an energy level with a different reference value (re: 1μPa^2-s). Thus, it is not directly comparable to other metrics that describe sound pressure levels (re: 1 μPa)[26].

2.3.4 Development of PTS Onset Acoustic Threshold Levels

The development of the PTS onset acoustic threshold levels consisted of the following the procedure described in Finneran 2015 (Appendix A) via the following steps:

[25] In this document, this metric is abbreviated dB_{peak}, which is equivalent to the ANSI abbreviation of L_{pk} (ANSI 2013). Note: Peak sound pressure level should not be confused with *maximum* root mean square sound pressure level.

[26] For more information and illustrations on metrics see Discovery of Sound in the Sea: http://www.dosits.org/science/advancedtopics/signallevels/.

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1. Identification of available data on marine mammal hearing and noise-induced hearing loss (e.g., Google Scholar, Web of Knowledge, Southall et al. 2007, Finneran 2015 references in listed in available reports/publications).

2. Methodology to derive marine mammal auditory weighting functions (described in more detail in Section 2.2.3 and Appendix A).

3. Evaluation and summary of currently available, published data (31 studies found in Table 10) on hearing loss associated with sound exposure in marine mammals.
   - Because no published measurements exist on PTS in marine mammals, TTS onset measurements and associated threshold levels were evaluated and summarized to extrapolate to PTS onset threshold levels.

   - Studies were summarized by dividing them into the following categories based on temporal characteristics of the sound at the source and functional hearing group studied:
     - Temporal Characteristics: Impulsive and Non-impulsive

     - Marine Mammal Functional Hearing Groups: LF Cetaceans, MF Cetaceans, HF Cetaceans, Phocid Pinnipeds, and Otariid Pinnipeds

4. Determination of TTS onset threshold level (RLs, in both peak pressure and SEL_{cum} metrics) for each individual where data were available based on methodology from Finneran 2015 for impulsive and non-impulsive sounds (Full detail in Appendix A).
   - Non-impulsive sounds:
     - TTS data from behavioral studies only were used, since those using AEP methodology are typically larger (e.g., up to 10 dB difference, Finneran et al. 2007) and considered to be representative (as illustrated in Appendix A, Figure 9)

     - TTS onset derived on a per individual basis by combining available data to create single TTS growth curve (e.g., dB TTS/dB noise) by frequency as a function of SEL_{cum}

     - TTS growth data were fit using the following function (Equation 4):

$$t(L) = m_1 \log_{10}\left[1 + 10^{(L-m_2)/10}\right] \quad \textbf{Equation 4}$$

where t is the amount of TTS, L is the SEL, and m_1 and m_2 are fitting parameters. This function has an increasing slope when $L < m_2$ and approaches a linear relationship for $L > m_2$ (Maslen 1981; Kastak

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Table 10: Currently available underwater marine mammal threshold shift peer reviewed studies.

References in Chronologic Order+	Sound Source (Sound Source Category)	Sound-Exposed Species (number of individuals^)
Kastak et al. 1999	Octave-band noise (non-impulsive)	California sea lion (1), northern elephant seal (1), & harbor seal (1)
Finneran et al. 2000	Explosion simulator (impulsive)*	Bottlenose dolphin (2) & beluga (1)
Schlundt et al. 2000	Tones (non-impulsive)	Bottlenose dolphin (5) & beluga (2)
Finneran et al. 2002	Seismic watergun (impulsive)	Bottlenose dolphin (1) & beluga (1)
Finneran et al. 2003	Arc-gap transducer (impulsive)*	California sea lion (2)
Nachtigall et al. 2003	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Nachtigall et al. 2004	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Finneran et al. 2005a	Tones (non-impulsive)	Bottlenose dolphin (2)
Kastak et al. 2005	Octave-band noise (non-impulsive)	California sea lion (1), northern elephant seal (1), & harbor seal (1)
Finneran et al. 2007a	Tones (non-impulsive)	Bottlenose dolphin (1)
Lucke et al. 2009	Single airgun (impulsive)	Harbor porpoise (1)
Mooney et al. 2009a	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Mooney et al. 2009b	Mid-frequency sonar (non-impulsive)	Bottlenose dolphin (1)
Finneran et al. 2010a	Tones (non-impulsive)	Bottlenose dolphin (2)
Finneran et al. 2010b	Tones (non-impulsive)	Bottlenose dolphin (1)
Finneran and Schlundt 2010	Tones (non-impulsive)	Bottlenose dolphin (1)
Popov et al. 2011a	Half-octave band noise (non-impulsive)	Yangtze finless porpoise (2)
Popov et al. 2011b	Half-octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2012a	Octave-band noise (non-impulsive)	Harbor seal (2)
Kastelein et al. 2012b	Octave-band noise (non-impulsive)	Harbor porpoise (1)
Finneran and Schlundt 2013	Tones (non-impulsive)	Bottlenose dolphin (2)
Popov et al. 2013	Half-octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2013a	Octave-band noise (non-impulsive)	Harbor seal (1)
Kastelein et al. 2013b	Tone (non-impulsive)	Harbor porpoise (1)
Popov et al. 2014	Half-octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2014a	1-2 kHz sonar (non-impulsive)	Harbor porpoise (1)
Kastelein et al. 2014b	6.5 kHz tone (non-impulsive)	Harbor porpoise (1)
Kastelein et al. 2015a	Impact pile driving (impulsive)	Harbor porpoise (1)

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Kastelein et al. 2015b	6-7 kHz sweeps (non-impulsive)	Harbor porpoise (1)
Finneran et al. 2015*	Multiple airgun shots (impulsive)*	Bottlenose dolphin (3)
Popov et al. 2015	Half-octave band noise (non-impulsive)	Beluga (1)

+Peer reviewed studies available and evaluated as of 15 July 2015.

^Note: Some individuals have been used in multiple studies.

*No incidents of temporary threshold shift were recorded in study.

et al. 2005; Finneran and Schlundt 2013). The linear portion of the function has a slope of $m_1/10$ and an intercept of m_2.

- TTS onset was defined as the SEL_{cum} value from the growth curve interpolated at a value of TTS = 6 dB. Only datasets where data were available with TS above and below 6 dB were used to define TTS onset (i.e., extrapolation was not performed on datasets not meeting this criterion).

- Interpolation was used to estimate SEL_{cum} necessary to induce 6 dB of TTS (Appendix A, Figures 10-13 and Table 6 summarize marine mammal growth rate data, with Figures illustrating at what SEL 6 dB of TTS occurs). Note: Appendix A, Figures 18-20 illustrate available marine mammal TTS data in relation to the composite audiogram and exposure function.

- Finally, weighted auditory threshold levels for TTS onset were determined by the minimum value of the exposure function (Equation 2), which is mathematically equivalent to $K + C$ (Table 11).

Table 11: TTS onset auditory threshold levels for non-impulsive sounds.

Functional Hearing Group	K (dB)	C (dB)	Weighted TTS onset acoustic threshold level (SEL_{cum})
Low-frequency (LF) cetaceans	187	0.43	187 dB
Mid-frequency (MF) cetaceans	178	1.02	179 dB
High-frequency (HF) cetaceans	149	1.63	151 dB
Phocid pinnipeds (underwater)	181	0.38	181 dB
Otariid pinnipeds (underwater)	198	0.49	198 dB

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- Impulsive sounds:
  - Available TTS data for these types of sources (MF and HF cetaceans only) were weighted based on derive marine mammal auditory weighting functions for the appropriate functional hearing group.

  - For functional hearing groups, where impulsive TTS onset data did not exist (LF cetaceans and phocid and otariid pinnipeds), Finneran (2015) derived impulsive TTS onset acoustic threshold levels using the relationship between non-impulsive TTS onset acoustic threshold levels and impulsive TTS onset acoustic threshold levels for MF and HF cetaceans via the relationship (Equation 5; Similar to what was presented in Southall et al. 2007):

$$G_s - G_i = \overline{C_s} - \overline{C_i} \quad \textbf{Equation 5}$$

where G represents the acoustic threshold level for a species group for which impulsive TTS onset data are not available and $\bar{C}$ indicates the mean of the difference MF and HF cetacean acoustic threshold levels (i.e., 10 dB[27]). Subscript s indicates the steady-state (non-impulsive) acoustic threshold level and the subscript i indicates the impulsive acoustic threshold level.

A similar approach was investigated for the peak pressure threshold, resulting in -45 dB, which was considered unrealistic. Instead, the MF cetacean peak pressure data were used for all other functional hearing groups.

5. Extrapolation for PTS onset threshold level (in both peak pressure and SEL_{cum} metrics) based on data from humans and terrestrial mammals, with the assumption that the mechanisms associated with noise-induced threshold shifts in marine mammals is similar, if not identical, to that recorded in terrestrial mammals.
   - Non-impulsive sounds:
     - PTS onset acoustic threshold levels were estimated using TTS growth rates based on those marine mammal studies were 20 dB or more of a TS was induced. This was done to estimate more accurately PTS onset, since using growth rates based on smaller TSs are often shallower than compared to those inducing greater TSs (See Appendix A, Figures 10-13 for details on available data for marine mammal growth rates).

[27] Specifically, there was an 8 dB difference for MF cetaceans (i.e., 179 dB and 172 dB SEL_{cum}) and a 9 dB difference for HF cetaceans (i.e., 151 dB and 139 dB SEL_{cum}).

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- PTS onset was derived using the same methodology as TTS onset, with PTS onset defined as the SEL value from the fitted curve at a TTS of 40 dB.

- Offset between TTS and PTS onset acoustic threshold levels were examined. Data were available for nine scenarios, including one from pinniped airborne exposure (Table 12):

Table 12: Summary of cetacean TTS growth data (Finneran 2015).

Species (Subject)	Frequency	TTS onset (SEL_{cum})	PTS onset (SEL_{cum})	TTS-PTS Offset	Reference
Mid-Frequency (MF) Cetaceans					
Bottlenose dolphin (BLU)	3 kHz	206 dB	240 dB	34 dB	Finneran et al. 2010a
Bottlenose dolphin (BLU)	14.1 kHz	176 dB	213 dB	37 dB	Finneran and Schlundt 2013
	20 kHz	181 dB	212 dB	31 dB	
	28.3 kHz	177 dB	190 dB	13 dB	
Beluga (female)	22.5 kHz	184 dB	206 dB	22 dB	Popov et al. 2014
High-Frequency (HF) Cetaceans					
Harbor porpoise (02)	~1.5 kHz	191 dB	207 dB	16 dB	Kastelein et al. 2014a
Harbor porpoise (02)	6.5 kHz	176 dB	204 dB	28 dB	Kastelein et al. 2014b
Harbor porpoise (02)	~6.5 kHz	180 dB	197 dB	17 dB	Kastelein et al. 2015b
Otariid Pinnipeds (Air)					
California sea lion (Rio)	2.5 kHz	159 dB re: 20 µPa	176 dB re: 20 µPa	17 dB	Kastak et al. 2007

[+] TTS growth rates are expressed as dB of TTS/dB of noise. TTS growth rates are defined as the linear portion of the growth rate function (Equation 4), with a slope of $m_1/10$.

- From these scenarios, the TTS-PTS offset ranged from 13 to 37 dB (mean/median: 25 dB for cetacean data; if airborne pinniped growth rate data is included: 23.8 dB mean/22 dB median). Thus, based on these data, a 20 dB offset was used to estimate PTS onset acoustic threshold levels from TTS onset acoustic threshold levels for non-impulsive sources (i.e., 20 dB was added to K to determine PTS onset, assuming the shape of the PTS exposure function for each functional hearing group is identical to the TTS exposure function for that functional hearing group).

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- Impulsive sounds: Based on limited available marine mammal impulsive data, the relationships previously derived in Southall et al. (2007), based on terrestrial mammal growth rates (Henderson and Hamernik 1982; Henderson and Hamernik 1986; Price and Wansack 1989; Levine et al. 1998; Henderson et al. 2008, was used to predict PTS onset:
    - Resulting in an approximate 15 dB difference between TTS and PTS onset acoustic threshold levels in SEL_{cum} metric (Equation 6):

(40 dB TS [PTS onset] – 6 dB TS [TTS onset]) / [2.3 dB of TTS/dB of noise exposure] = 15 dB
Equation 6

Southall et al. (2007) recommended a 6 dB of TTS/dB of noise growth rate for peak pressure acoustic threshold levels. This recommendation was based on several factors, including ensuring that the peak pressure acoustic threshold level did not unrealistically exceed the cavitation threshold of water.

- Resulting in an approximate 6 dB difference between TTS and PTS onset acoustic threshold levels in peak pressure metric (Equation 7):

(40 dB TS [PTS onset] – 6 dB TS [TTS onset]) / [6 dB of TTS/dB of noise exposure] = 6 dB
Equation 7

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III. U.S. REGULATORY CONTEXT FOR ACOUSTIC THRESHOLD LEVELS FOR MARINE MAMMALS

NOAA has compiled, interpreted and synthesized the best available science to produce updated threshold levels for the onset of both PTS (Table A) and TTS (Appendix A, Table 10) in marine mammals from acute, incidental exposure to underwater sound. NOAA uses this information to help quantify "take" and to conduct more comprehensive effects analyses under several statutes. These updated acoustic threshold levels do not represent the entirety of the comprehensive effects analysis, but rather serve as one tool (e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the ultimate effects of any particular type of impact on an individual's fitness, population assessments, etc.) to help evaluate the effects of a proposed action on marine mammal hearing and make findings required by NOAA's various statutes.

Marine Mammal Protection Act (MMPA) and Endangered Species Act (ESA)

NOAA equates the onset of PTS, which is an auditory injury, with "Level A Harassment" as defined in the MMPA and with "harm" as defined in ESA regulations, such that exposing an animal to weighted received sound levels at or above the indicated PTS threshold is considered to result in these two types of "take" (i.e., Level A Harassment under the MMPA and harm under ESA).

As explained below, NOAA does not consider a TTS to be an auditory injury, under the MMPA or ESA, and thus it does not qualify as Level A harassment or harm. Nevertheless, TTS is an adverse effect that constitutes another kind of "take" under those statutes: "Level B Harassment" under the MMPA and "harassment" under the ESA. MMPA Level B harassment and ESA harassment are broad categories that encompass not only TTS but also other effects such as behavioral impacts, which almost always involve a lower onset threshold level than that for onset of TTS. In quantifying take by Level B harassment or harassment, NOAA considers *all* effects that fall into those categories of take, not just TTS. NOAA currently is in the process of developing updated threshold levels for the onset of behavioral effects. When that process is completed, TTS will be addressed for purposes of take quantification. In the meantime, the TTS threshold levels presented in the Guidance represent the compilation, interpretation, and synthesis of the best available science and will be used in the comprehensive effects analyses under the MMPA and the ESA and *may* inform the development of mitigation and monitoring.

National Marine Sanctuaries Act (NMSA)

The broad definition of "injury" under the NMSA regulations includes both PTS and TTS (as well as other adverse changes in physical or behavioral characteristics that are not addressed in this document).

3.1 BACKGROUND: APPLICABLE STATUTORY AND REGULATORY STANDARDS, DEFINITIONS AND PROCESSES

3.1.1 Marine Mammal Protection Act

The MMPA prohibits the take of marine mammals, with certain exceptions, one of which is the issuance of incidental take authorizations (ITAs). Sections 101(a)(5)(A) & (D) of the MMPA (16 U.S.C. 1361 *et seq.*) direct the Secretary of Commerce to allow, upon request, the incidental, but not intentional, taking of small numbers of marine mammals by U.S. citizens who engage in a specified activity (other than commercial fishing) within a specified geographical region if certain findings are made. Through delegation by the Secretary of Commerce, NMFS is required to authorize the incidental taking of marine mammals if it finds that the total taking will have a negligible impact on the species or stock(s) and will not have an unmitigable adverse impact on the availability of the species or stock(s) for certain subsistence uses. NMFS must also set forth the permissible methods of taking and

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requirements pertaining to the mitigation, monitoring, and reporting of such takings. (The "small numbers" and "specified geographical region" provisions do not apply to military readiness activities.)

The term "take" means to harass, hunt, capture, or kill, or attempt to harass, hunt, capture or kill any marine mammal. 16 U.S.C. § 1362(13).

Except with respect to certain activities described below, "harassment" means any act of pursuit, torment, or annoyance which:

- has the potential to injure a marine mammal or marine mammal stock in the wild ***[Level A Harassment]***, or

- has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding or sheltering ***[Level B Harassment]***.

*See id.*at 1362(18)(A)(i) & (ii) (emphasis added).

Congress amended the definition of "harassment" as it applies to a "military readiness activity" as follows (section 3(18)(B) of the MMPA):

- any act that injures or has the significant potential to injure a marine mammal or marine mammal stock in the wild ***[Level A Harassment***]; or

- any act that disturbs or is likely to disturb a marine mammal or marine mammal stock in the wild by causing disruption of natural behavioral patterns, including, but not limited to, migration, surfacing, nursing, breeding, feeding, or sheltering, to a point where such behavioral patterns are abandoned or significantly altered ***[Level B Harassment]***.

*See id.*at 1362(18)(B)(i) & (ii) (emphasis added).

The term "negligible impact" is defined as an impact resulting from the specified activity that cannot be reasonably expected to, and is not reasonably likely to, adversely affect the species or stock through effects on annual rates of recruitment or survival. 50 C.F.R. § 216.103.

In support of the analysis that is necessary to make the required statutory determinations, MMPA implementing regulations require ITA action proponents to provide NMFS with specific information. The updated acoustic threshold levels are particularly relevant to the following two of the fourteen required pieces of information:

- The ***type*** of incidental taking authorization that is being requested (i.e., takes by Level B Harassment only; ***Level A Harassment***; or serious injury/mortality) and the method of incidental taking;

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- By age, sex, and reproductive condition (if possible), the ***number*** of marine mammals (by species) that may be taken ***by each type*** of taking identified in paragraph (a)(5) of this section, and the number of times such takings by each type of taking are likely to occur.

50 CFR § 216.104 (emphasis added).

3.1.2 Endangered Species Act

Section 9 of the ESA prohibits the take of ESA-listed species, with limited exceptions. Section 7 of the ESA requires that each federal agency, in consultation with NMFS and/or the U.S. Fish and Wildlife Service (USFWS), ensure that any action authorized, funded, or carried out by the agency is not likely to jeopardize the continued existence of any endangered or threatened species or result in the destruction or adverse modification of designated critical habitat. *See* 16 U.S.C. § 1536(a)(2). Provided that NMFS or the USFWS reaches these conclusions through a "formal consultation" process, incidental take of ESA-listed species may be exempted from the Section 9 take prohibition through an "incidental take statement" that must specify the impact, i.e., the amount or extent, of the taking on the species. *See id.* at § 1536(b)(4). Incidental take statements must also include reasonable and prudent measures necessary or appropriate to minimize the impact, and the terms and conditions required to implement those measures.

Under ESA, "take" means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct. *See id.*at § 1532(19). "Harm" is defined in NMFS regulations as "an act which actually kills or injures fish or wildlife" (and can include significant habitat modification or degradation). *See* 50 C.F.R. § 222.102.

Under NMFS and the USFWS implementing regulations for Section 7 of the ESA, "jeopardize the continued existence of" means to engage in an action that reasonably would be expected, directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of a listed species in the wild by reducing the reproduction, numbers, or distribution of that species. *See id.*at § 402.02.

In support of the analysis necessary to conduct the consultation, the ESA implementing regulations state that in order to initiate formal consultation, the federal action agency must submit a written request for formal consultation to the Director (of NMFS or the USFWS) that includes, among other things, a description of the manner in which the action may affect any listed species. *See id.*at § 402.14(c).

3.1.3 National Marine Sanctuaries Act

Section 304(d) of the NMSA requires federal agencies whose actions are likely to destroy, cause the loss of, or injure a sanctuary resource to consult with the Office of National Marine Sanctuaries (ONMS) before taking the action. *See* 16 U.S.C. § 1434(d)(1). The

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NMSA defines sanctuary resource as "any living or nonliving resource of a national marine sanctuary that contributes to the conservation, recreational, ecological, historical, educational, cultural, archeological, scientific, or aesthetic value of the sanctuary."16 U.S.C. § 1432(8). Through the sanctuary consultation process, ONMS may recommend reasonable and prudent alternatives that will protect sanctuary resources. Recommended alternatives may include alternative locations, timing, and/or methods for conducting the proposed action. *See id.*at § 1434(d)(2). Monitoring may also be recommended to better characterize impacts to sanctuary resources or accompany mitigation. *See id.*

The term "injure" is defined in the ONMS implementing regulations as to "change adversely, either in the short or long term, a chemical, biological or physical attribute of, or the viability of." 15 C.F.R. § 922.3

In support of the analysis necessary to conduct the consultation, the NMSA requires that any federal agency proposing an action that may injure a sanctuary resource provide ONMS with a written statement ("sanctuary resource statement") describing the action and its potential effects on sanctuary resources. *See* 16 U.S.C. § 1434(d)(1)(B).

3.2 Application of Acoustic Threshold Levels for Permanent Threshold Shift

The acoustic threshold levels for PTS will be used in conjunction with sound source characteristics, environmental factors that influence sound propagation, anticipated marine mammal occurrence and behavior in the vicinity of the activity, as well as other available activity-specific factors, to estimate (acknowledging the gaps in scientific knowledge and the inherent uncertainties in a marine environment) the number of takes of marine mammals (Level A harassment and harm under the MMPA and ESA, respectively) and facilitate compliance with the MMPA, ESA, and NMSA as described above.

NOAA will use the same PTS threshold levels in the identification and quantification of MMPA Level A harassment for both military readiness and non-military readiness activities. Because the acoustic threshold levels for PTS predict the onset of PTS, they are inclusive of the "potential" and "significant potential" language in the two definitions of Level A harassment. The limited data now available do not support the parsing out of a meaningful quantitative difference between the "potential" and "significant potential" for injury and, therefore, the designated PTS threshold levels will be treated as Level A harassment for both types of activities.

Estimating the numbers of take by Level A harassment and harm is one component of the fuller analyses that inform NOAA's "negligible impact" and "jeopardy" determinations under the MMPA and ESA, respectively, as well as "likely to injure" or "may affect" determinations under the NMSA. Last, the PTS threshold levels may be used to inform the development of mitigation and monitoring measures (such as shut-down zones) pursuant to the MMPA, ESA, or NMSA.

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When initiating any of the MMPA, ESA, or NMSA processes described above, agencies and other action proponents should utilize the PTS threshold levels and methods outlined in Section II of this document, in combination with activity-specific information, to predict whether, and if so how many, instances of PTS are expected to occur.

3.2.1 Acoustic Threshold Levels for Temporary Threshold Shift

As previously stated, NOAA does not consider a TTS an auditory injury, under the MMPA and ESA, based on the work of a number of investigators that have measured TTS before and after exposure to intense sound. For example, Ward (1997) suggested that a TTS is within the normal bounds of physiological variability and tolerance and does not represent physical injury. In addition, Southall et al. (2007) indicates that although PTS is a tissue injury, TTS is not because the reduced hearing sensitivity following exposure to intense sound results primarily from fatigue, not loss, of cochlear hair cells and supporting structures, and is reversible. Accordingly, NMFS does not consider TTS as Level A harassment under the MMPA or harm under the ESA. Rather, TTS is considered take by Level B harassment under the MMPA and harassment under the ESA, which will be the subject of future guidance. However, TTS (along with PTS and behavioral impacts) is considered injury under the broad definition of the term "injury" in NMSA regulations.

NOAA is aware of recent studies by Kujawa and Liberman (2009) and Lin et al. (2011), which found that despite completely reversible threshold shifts that leave cochlear sensory cells intact, large (but temporary) threshold shifts could cause synaptic level changes and delayed cochlear nerve degeneration in mice and guinea pigs. However, the large threshold shifts (i.e., maximum 40 dB[28]) that led to the synaptic changes shown in these studies are in the range of the large shifts used by Southall et al. (2007) and here in the Guidance to define PTS onset (i.e., 40 dB). It unknown whether smaller levels of TTS would lead to similar changes or the long-term implications of irreversible neural degeneration. The effects of sound exposure on the nervous system is complex, and this will be re-examined, as more data become available.

The occurrence of, and estimated number of, TTS takes is one component of the larger analysis that informs NOAA's "negligible impact" and "jeopardy" determinations under the MMPA and ESA, respectively, as well as "likely to injure" or "may affect" determinations under the NMSA. TTS threshold levels also may be used to inform the development of mitigation and monitoring measures pursuant to the MMPA, ESA, or NMSA.

Note: This document constitutes a statement of NOAA's current practice for assessing Level A Harassment and harm pursuant to the MMPA and ESA, respectively, and one kind of injury under the NMSA, from auditory impacts. NOAA recommends that federal agencies and prospective action proponents evaluating these types of impacts for the purposes of engaging in the aforementioned statutory processes also use these thresholds in

[28] The exposure levels used in Lin et al. 2011 were "within 3 dB of the boundary between reversibility and irreversibility, at least with respect to the threshold for ABRs and DPOAEs."

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the manner described here. However, this Guidance does not create or confer any rights for or on any person, or operate to bind the public. An alternative approach may be proposed (by federal agencies or prospective action proponents) and used if case-specific information/data indicate that the alternative approach is likely to produce a more accurate estimate of Level A Harassment, harm, or auditory injury for the project being evaluated and if NOAA determines the approach satisfies the requirements of the applicable statutes and regulations.

IV. UPDATE OF ACOUSTIC GUIDANCE AND ACOUSTIC THRESHOLD LEVELS

Research on the effects of anthropogenic sound on marine mammals has increased dramatically since the adoption of NOAA's previous acoustic threshold levels and will likely continue to increase in the future. As such, this document will be reviewed periodically and updated as appropriate to reflect the compilation, interpretation, and synthesis of the best available science.

NOAA's initial approach for updating current acoustic threshold levels consisted of providing acoustic threshold levels for underwater PTS onset for marine mammals. As more data become available, acoustic thresholds may be established for added protected species, such as sea turtles and marine fishes. As with this document, public review and outside peer review will be integral to the development and refinement of acoustic thresholds.

4.1 PROCEDURE AND TIMELINE FOR UPDATING ACOUSTIC THRESHOLD LEVELS

NOAA will convene staff from our various offices, regions, and science centers, and re-evaluate and update acoustic threshold levels at least every three to five years as new data become available and as deemed appropriate, providing opportunities for adaptive management. In addition to evaluating new, relevant scientific studies, NOAA will also periodically re-examine basic concepts and definitions (e.g., functional hearing groups, PTS, TTS, weighting functions), appropriate metrics, temporal and spatial considerations, and other relevant topics. Updates will be posted at http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm

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APPENDIX A: NAVY TECHNICAL REPORT

The U.S. Navy's entire Technical Report (Finneran 2015), regarding methodology for deriving marine mammal auditory weighting functions and acoustic threshold levels, is included for reference in Appendix A.

Note: Literature cited in this section are included at the end of this Appendix (i.e., not all references found in this Appendix are included in the Literature Cited for the Guidance).

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July 2015

Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores

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SSC Pacific

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EXECUTIVE SUMMARY

The US Navy's Tactical Training Theater Assessment and Planning (TAP) Program addresses environmental challenges that affect Navy training ranges and operating areas. As part of the TAP process, acoustic effects analyses are conducted to estimate the potential effects of Navy activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects of underwater sound on cetaceans (e.g., baleen whales, dolphins, porpoises) and marine carnivores (e.g., seals and sea lions) exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns for Phase 3 of the TAP Program. Since the derivation of TAP Phase 2 acoustic criteria and thresholds, important new data have been obtained related to the effects of noise on marine mammal hearing. Therefore, for Phase 3, new criteria and thresholds for the onset of temporary and permanent hearing loss have been developed, following a consistent approach for all species of interest and utilizing all relevant, available data. The effects of noise frequency on hearing loss are incorporated by using auditory weighting functions to emphasize noise at frequencies where a species is more sensitive to noise and de-emphasize noise at frequencies where susceptibility is low.

Cetaceans and marine carnivores were divided into five groups for analysis: low-frequency cetaceans (group LF: mysticetes), mid-frequency cetaceans (group MF: delphinids, beaked whales, sperm whales), high-frequency cetaceans (group HF: porpoises, river dolphins), phocids (group PW: true seals), otariids and other non-phocid marine carnivores in water (group OW: sea lions, walruses, otters, polar bears).

For each group, a frequency-dependent weighting function and numeric thresholds for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) were derived from available data describing hearing abilities and effects of noise on marine mammals. The resulting weighting functions are illustrated in Figure E-1; Table E-1 summarizes the parameters necessary to calculate the weighting function amplitudes. For Navy Phase 3 analyses, the onset of TTS is defined as a TTS of 6 dB measured approximately 4 min after exposure. PTS is assumed to occur from exposures resulting in 40 dB or more of TTS measured approximately 4 min after exposure. Exposures just sufficient to cause TTS or PTS are denoted as "TTS onset" or "PTS onset" exposures.

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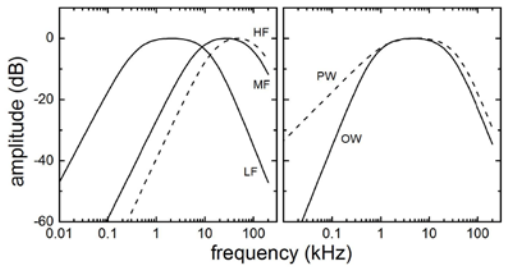


Figure E-1. Navy Phase 3 weighting functions for all species groups. Parameters required to generate the functions are provided in Table E-1.

Table E-1. Summary of weighting function parameters and TTS/PTS thresholds. SEL thresholds are in dB re 1 µPa^{2}s and peak SPL thresholds are in dB re 1 µPa.

$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	*a*	*b*	f_1 (kHz)	f_2 (kHz)	*C* (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1.5	2	0.38	13	0.43	187	207	177	224	192	230
MF	1.6	2	7.4	110	1.02	179	199	172	224	187	230
HF	1.7	2	16	150	1.63	151	171	139	196	154	202
OW	2	2	0.77	27	0.49	198	218	188	224	203	230
PW	0.8	2	1.3	37	0.38	181	201	171	224	186	230

To compare the Phase 3 weighting functions and TTS/PTS thresholds to those used in TAP Phase 2 analyses, both the weighting function shape and the weighted threshold values must be taken into account; the weighted thresholds by themselves only indicate the TTS/PTS threshold at the most susceptible frequency (based on the relevant weighting function). In contrast, the TTS/PTS *exposure functions* incorporate both the shape of the weighting function and the weighted threshold value, they provide the best means of comparing the frequency-dependent TTS/PTS thresholds for Phase 2 and 3. Figures E-2 and E-3 compare the TTS/PTS exposure functions for non-impulsive sounds (e.g., sonars) and impulsive sounds (e.g., explosions), respectively, used in TAP Phase 2 and Phase 3.

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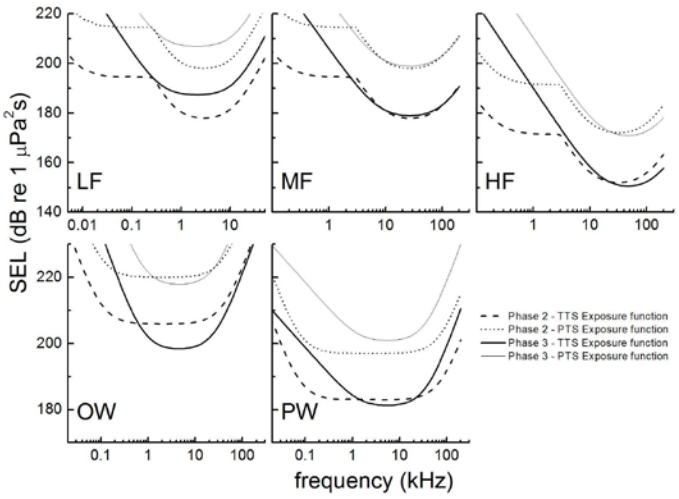


Figure E-2. TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table 10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table 10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

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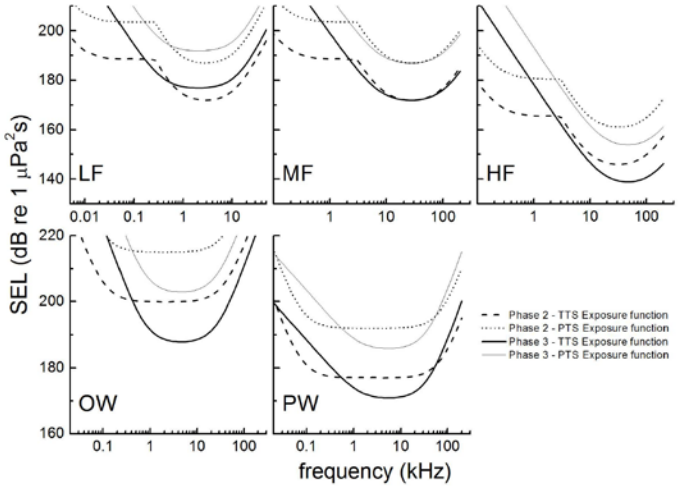


Figure E-3. TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table 10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table 10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

The most significant differences between the Phase 2 and Phase 3 functions include: (1) Thresholds at low frequencies are higher for Phase 3 compared to Phase 2. This is because the Phase 2 weighting functions utilized the "M-weighting" functions at lower frequencies, where no TTS existed at that time. Since derivation of the Phase 2 weighting functions, additional data have been collected to support the use of new functions more similar human auditory weighting functions. (2) The LF cetacean thresholds are higher at all frequencies compared to those used in Phase 2. This change reflects an adjustment to the TTS/PTS thresholds to take into account the suspected elevated thresholds in LF cetaceans relative to MF cetaceans.

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1. INTRODUCTION

1.1. Overview

The US Navy's Tactical Training Theater Assessment and Planning (TAP) Program addresses environmental challenges that affect Navy training ranges and operating areas. As part of the TAP process, acoustic effects analyses are conducted to estimate the potential effects of Navy training and testing activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects on cetaceans and marine carnivores exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns for Phase 3 of the TAP Program. The weighted threshold values and auditory weighting function shapes are summarized in Section 12.

1.2. Impulse vs. non-impulsive noise

When analyzing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulse noise — noise with high peak sound pressure, short duration, fast rise-time, and broad frequency content — or non-impulsive (i.e., steady-state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are considered to be non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources. Note that the terms non-impulsive or steady-state do not necessarily imply long duration signals, only that the acoustic signal has sufficient duration to overcome starting transients and reach a steady-state condition. For harmonic signals, sounds with duration greater than approximately 5 to 10 cycles are generally considered to be steady-state.

1.3. Noise-induced threshold shifts

Exposure to sound with sufficient duration and sound pressure level (SPL) may result in an elevated hearing threshold (i.e., a loss of hearing sensitivity), called a noise-induced threshold shift (NITS). If the hearing threshold eventually returns to normal, the NITS is called a temporary threshold shift (TTS); otherwise, if thresholds remain elevated after some extended period of time, the remaining NITS is called a permanent threshold shift (PTS). TTS and PTS data have been used to guide the development of safe exposure guidelines for people working in noisy environments. Similarly, TTS and PTS criteria and thresholds form the cornerstone of Navy analyses to predict auditory effects in marine mammals incidentally exposed to intense sound during naval activities.

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1.4. Auditory weighting functions

Animals are not equally sensitive to noise at all frequencies. To capture the frequency-dependent nature of the effects of noise, *auditory weighting functions* are used. Auditory weighting functions are mathematical functions used to emphasize frequencies where animals are more susceptible to noise exposure and de-emphasize frequencies where animals are less susceptible. The functions may be thought of as frequency-dependent filters that are applied to a noise exposure before a single, weighted SPL or sound exposure level (SEL) is calculated. The filter shapes are normally "band-pass" in nature; i.e., the function amplitude resembles an inverted "U" when plotted versus frequency. The weighting function amplitude is approximately flat within a limited range of frequencies, called the "pass-band," and declines at frequencies below and above the pass-band.

Auditory weighting functions for humans were derived from equal loudness contours — curves that show the combinations of SPL and frequency that result in a sensation of equal loudness in a human listener. Equal loudness contours are in turn created from data collected during loudness comparison tasks. Analogous tasks are difficult to perform with non-verbal animals; as a result, true equal loudness contours are available for only a single marine mammal (a dolphin) across a limited range of frequencies (2.5 to 113 kHz) (Finneran and Schlundt, 2011). In lieu of performing loudness comparison tests, reaction times to tones can be measured, under the assumption that reaction time is correlated with subjective loudness (Stebbins, 1966; Pfingst et al., 1975). From the reaction time vs. SPL data, curves of equal response latency can be created and used as proxies for equal loudness contours.

Just as human damage risk criteria use auditory weighting functions to capture the frequency-dependent aspects of noise, US Navy acoustic impact analyses use weighting functions to capture the frequency-dependency of TTS and PTS in marine mammals.

1.5. TAP Phase 3 weighting functions and TTS/PTS thresholds

Navy weighting functions for TAP Phase 2 (Finneran and Jenkins, 2012) were based on the "M-weighting" curves defined by Southall et al. (2007), with additional high-frequency emphasis for cetaceans based on equal loudness contours for a bottlenose dolphin (Finneran and Schlundt, 2011). Phase 2 TTS/PTS thresholds also relied heavily on the recommendations of Southall et al. (2007), with modifications based on preliminary data for the effects of exposure frequency on dolphin TTS (Finneran, 2010; Finneran and Schlundt, 2010) and limited TTS data for harbor porpoises (Lucke et al., 2009; Kastelein et al., 2011).

Since the derivation of TAP Phase 2 acoustic criteria and thresholds, new data have been obtained regarding marine mammal hearing (e.g., Ghoul and Reichmuth, 2014; Ketten, 2014; Ketten and Mountain, 2014; Sills et al., 2014; Cranford and Krysl, 2015), marine mammal equal latency contours (e.g., Wensveen et al., 2014; Mulsow et al., 2015), and the potential effects of noise on marine mammal hearing (e.g., Kastelein et al., 2012b; Kastelein et al., 2012a; Finneran and Schlundt, 2013; Kastelein et al., 2013a; Kastelein et

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al., 2013b; Popov et al., 2013; Kastelein et al., 2014b; Kastelein et al., 2014a; Popov et al., 2014; Finneran et al., 2015; Kastelein et al., 2015b). As a result, new weighting functions and TTS/PTS thresholds have been developed for Phase 3. The new criteria and thresholds are based on all relevant data and feature a consistent approach for all species of interest.

Cetaceans and marine carnivores were divided into five groups for analysis. For each group, frequency-dependent weighting function and numeric thresholds for the onset of TTS and PTS were derived from available data describing hearing abilities and effects of noise on marine mammals. Measured or predicted auditory threshold data, as well as measured equal latency contours, were used to approximate weighting function shapes in each group. For species groups for which TTS data are available, the weighting function parameters were adjusted to provide the best fit to the experimental data. The same methods were then applied to other species for whom TTS data do not exist.

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2. WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

The shapes of the Phase 3 auditory weighting functions are based on a generic band-pass filter described by

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}, \quad (1)$$

where $W(f)$ is the weighting function amplitude (in dB) at the frequency f (in kHz). The shape of the filter is defined by the parameters C, f_1, f_2, a, and b (Figs. 1 and 2, left panels):

C *weighting function gain* (dB). The value of C defines the vertical position of the curve. Changing the value of C shifts the function up/down. The value of C is often adjusted to set the maximum amplitude of the weighting function to 0 dB.

f_1 *low-frequency cutoff* (kHz). The value of f_1 defines the lower limit of the filter pass-band; i.e., the lower frequency at which the weighting function amplitude begins to decline or "roll-off" from the flat, central portion of the curve. The specific amplitude at f_1 depends on the value of a. Decreasing f_1 will enlarge the pass-band of the function and increase the flat, central portion of the curve.

f_2 *high-frequency cutoff* (kHz). The value of f_2 defines the upper limit of the filter pass-band; i.e., the upper frequency at which the weighting function amplitude begins to roll-off from the flat, central portion of the curve. The amplitude at f_2 depends on the value of b. Increasing f_2 will enlarge the pass-band of the function and increase the flat, central portion of the curve.

a *low-frequency exponent* (dimensionless). The value of a defines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As the frequency decreases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of $20a$ dB/decade. Larger values of a result in lower amplitudes at f_1 and steeper rolloffs at frequencies below f_1.

b *high-frequency exponent* (dimensionless). The value of b defines the rate at which the weighting function amplitude declines with frequency at the upper frequencies. As the frequency increases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of $-20b$ dB/decade. Larger values of b result in lower amplitudes at f_2 and steeper rolloffs at frequencies above f_2.

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If $a = 2$ and $b = 2$, Eq. (1) is equivalent to the functions used to define Navy Phase 2 Type I and EQL weighting functions, M-weighting functions, and the human C-weighting function (American National Standards Institute (ANSI), 2001; Southall et al., 2007; Finneran and Jenkins, 2012). The change from fixed to variable exponents for Phase 3 was done to allow the low- and high-frequency rolloffs to match experimental data when available. During implementation, the weighting function defined by Eq. (1) is used in conjunction with a weighted threshold for TTS or PTS expressed in units of SEL.

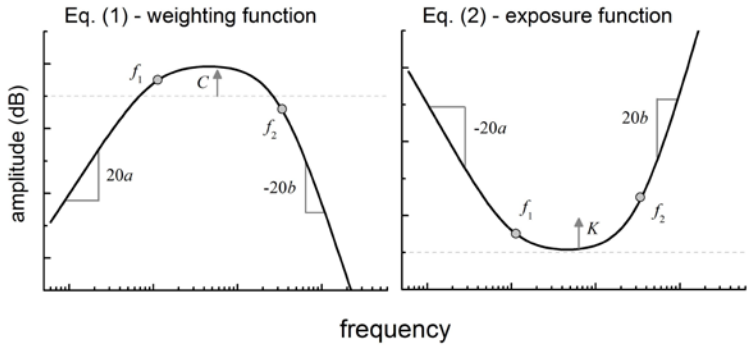
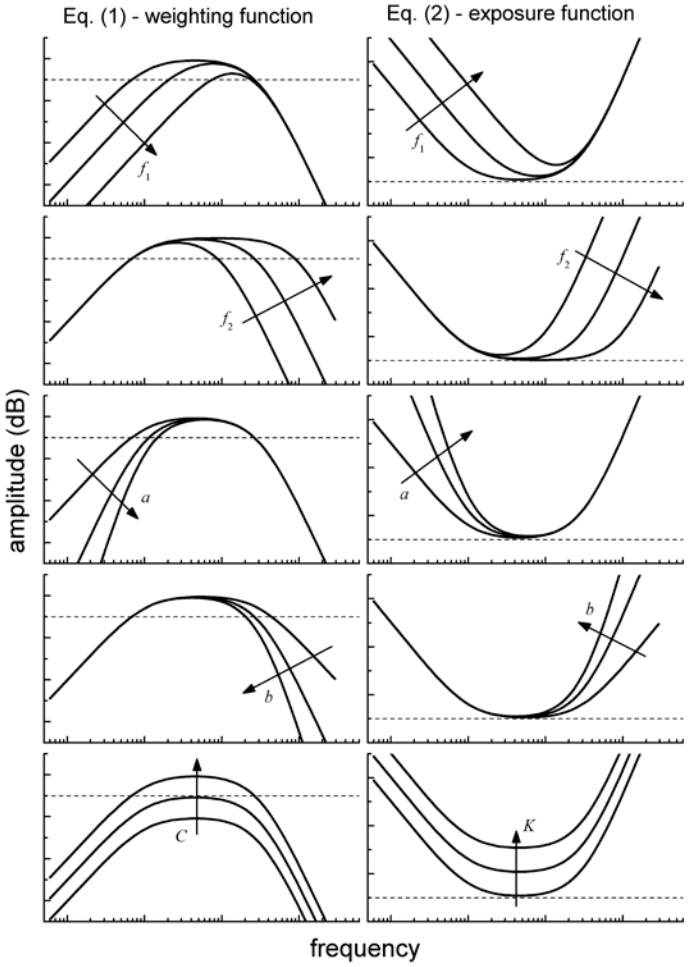


Figure 1. Examples of (left) weighting function amplitude described by Eq. (1) and (right) exposure function described by Eq. (2). The parameters f_1 and f_2 specify the extent of the filter pass-band, while the exponents a and b control the rate of amplitude change below f_1 and above f_2, respectively. As the frequency decreases below f_1 or above f_2, the amplitude approaches linear-log behavior with a slope magnitude of 20a or 20b dB/decade, respectively. The constants C and K determine the vertical positions of the curves.

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283 **Figure 2.** Influence of parameter values on the resulting shapes of the weighting functions (left) and
284 exposure functions (right). The arrows indicate the direction of change when the designated parameter is
285 increased.

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For developing and visualizing the effects of the various weighting functions, it is helpful to invert Eq. (1), yielding

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}, \quad (2)$$

where $E(f)$ is the acoustic exposure as a function of frequency f, the parameters f_1, f_2, a, and b are identical to those in Eq. (1), and K is a constant. The function described by Eq. (2) has a "U-shape" similar to an audiogram or equal loudness/latency contour (Figs. 1 and 2, right panels). If K is adjusted to set the minimum value of the curve to the weighted threshold for the onset of TTS or PTS, Eq. (2) reveals the manner in which the exposure necessary to cause TTS or PTS varies with frequency. Equation (2) therefore allows the frequency-weighted threshold values to be directly compared to TTS data. The function defined by Eq. (2) is referred to as an *exposure function*, since the curve defines the acoustic exposure that equates to TTS or PTS as a function of frequency. To illustrate the relationship between weighting and exposure functions, Fig. 3 shows the Navy Phase 2 weighting function [Eq. (1), left panel] and TTS exposure function [Eq. (2), right panel] for mid-frequency cetaceans exposed to sonars.

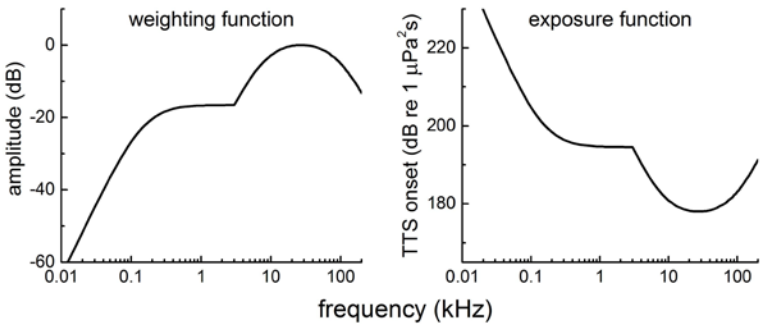


Figure 3. (left panel) Navy Phase 2 weighting function for the mid-frequency cetacean group. This function was used in conjunction with a weighted TTS threshold of 178 dB re 1 µPa^{2}s. For narrowband signals, the effective, weighted TTS threshold at a particular frequency is calculated by adding the weighting function amplitude at that frequency to the weighted TTS threshold (178 dB re 1 µPa^{2}s). To visualize the frequency-dependent nature of the TTS threshold, the weighting function is inverted and the minimum value set equal to the weighted TTS threshold. This is illustrated in the right panel, which shows the SEL required for TTS onset as a function of frequency. The advantage of this representation is that it may be directly compared to TTS onset data at different exposure frequencies.

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3. METHODOLOGY TO DERIVE FUNCTION PARAMETERS

Weighting and exposure functions are defined by selecting appropriate values for the parameters C, K, f_1, f_2, a, and b in Eqs. (1) and (2). Ideally, these parameters would be based on experimental data describing the manner in which the onset of TTS or PTS varied as a function of exposure frequency. In other words, a weighting function for TTS should ideally be based on TTS data obtained using a range of exposure frequencies, species, and individual subjects within each species group. However, at present, there are only limited data for the frequency-dependency of TTS in marine mammals. Therefore, weighting and exposure function derivations relied upon auditory threshold measurements (audiograms), equal latency contours, and predicted audiograms from anatomically based models, as well as TTS data when available.

Weighting and exposure function derivation consisted of the following steps:

1. Cetaceans and marine carnivores were divided into five groups based on auditory, ecological, and phylogenetic relationships among species.

2. For each species group, a representative, composite audiogram (a graph of hearing threshold vs. frequency) was derived.

3. The exponent a was defined using the smaller of the low-frequency slope from the composite audiogram or the low-frequency slope of equal latency contours. The exponent b was set equal to two.

4. The frequencies f_1 and f_2 were defined as the frequencies at which the composite threshold values are ΔT-dB above the lowest threshold value. The value of ΔT was chosen to minimize the mean-squared error between Eq. (2) and the non-impulsive TTS data for the mid- and high-frequency cetacean groups.

5. For species groups for which TTS onset data exist, K was adjusted to minimize the squared error between Eq. (2) and the steady-state (non-impulsive) TTS onset data. For other species, K was defined to provide the best estimate for the TTS onset at a representative frequency.

6. The constant C was defined to set the peak amplitude of the function defined by Eq. (1) to zero, and the weighted threshold for onset TTS was determined from the minimum value of the TTS exposure function.

8. The weighted threshold for PTS was derived for each group by adding a constant value (20 dB) to the weighted TTS thresholds. The constant was based on estimates of the difference in exposure levels between TTS onset and PTS onset (i.e., 40 dB of TTS) obtained from the marine mammal TTS growth curves.

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9. For the mid- and high-frequency cetaceans, weighted TTS and PTS thresholds for explosives and other impulsive sources were obtained from the available impulse TTS data. For other groups, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the mid- and high-frequency cetaceans.

The remainder of this document addresses these steps in detail.

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4. SPECIES GROUPS

Cetaceans and marine carnivores were divided into five groups (Table 1), with the same weighting function and TTS/PTS thresholds used for all species within a group. Species were grouped by considering their known or suspected audible frequency range, auditory sensitivity, ear anatomy, and acoustic ecology (i.e., how they use sound), as has been done previously (e.g., Ketten, 2000; Southall et al., 2007; Finneran and Jenkins, 2012).

4.1. Low-frequency (LF) cetaceans

The low-frequency cetacean group contains all of the mysticetes (baleen whales). Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from observed vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system. A natural division may exist within the mysticetes, with some species (e.g., blue, fin) having better low-frequency sensitivity and others (e.g., humpback, minke) having better sensitivity to higher frequencies; however, at present the uncertainties in the auditory models are comparable in magnitude to the suspected differences in hearing abilities. Therefore, a single species group is used for all mysticetes.

4.2. Mid-frequency (MF) cetaceans

This group contains most delphinid species (e.g., bottlenose dolphin, common dolphin, killer whale, pilot whale), beaked whales, and sperm whales (but not pygmy and dwarf sperm whales of the genus Kogia, which are treated as high-frequency species). Hearing sensitivity has been directly measured for a number of species within this group using psychophysical (behavioral) or auditory evoked potential (AEP) measurements.

4.3. High-frequency (HF) cetaceans

This group contains the porpoises, river dolphins, pygmy/dwarf sperm whales, *Cephalorhynchus* species, and some *Lagenorhynchus* species. Hearing sensitivity has been measured for several species within this group using behavioral or AEP measurements. High-frequency cetaceans generally possess a higher upper-frequency limit and better sensitivity at high frequencies compared to the mid-frequency cetacean species.

4.4. Phocids

This group contains all earless seals or "true seals," including all Arctic and Antarctic ice seals, harbor or common seals, gray seals and inland seals, elephant seals, and monk seals. Underwater hearing thresholds exist for some Northern Hemisphere species in this group.

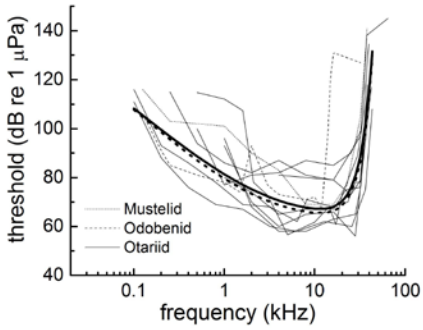
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392 **4.5. Otariids and other non-phocid marine carnivores**

393 This group contains all eared seals (fur seals and sea lions), walruses, sea otters, and polar
394 bears. The division of marine carnivores by placing phocids in one group and all others
395 into a second group was made after considering auditory anatomy and measured
396 audiograms for the various species and noting the similarities between the non-phocid
397 audiograms (Fig. 4). Underwater hearing thresholds exist for some Northern Hemisphere
398 species in this group.

399



400

401 **Figure 4.** Comparison of Otariid, Mustelid, and Odobenid psychophysical hearing thresholds measured
402 underwater. The thick, solid line is the composite audiogram based on data for all species. The thick,
403 dashed line is the composite audiogram based on the otariids only.

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404 **Table 1.** Species group designations for Navy Phase 3 auditory weighting functions.

Code	Name	Members
LF	Low-frequency cetaceans	Family Balaenidae (right and bowhead whales) Family Balaenopteridae (rorquals) Family Eschrichtiidae (gray whale) Family Neobalaenidae (pygmy right whale)
MF	Mid-frequency cetaceans	Family Ziphiidae (beaked whales) Family Physeteridae (Sperm whale) Family Monodontidae (Irrawaddy dolphin, beluga, narwhal) Subfamily Delphininae (white-beaked/white-sided/ Risso's/bottlenose/spotted/spinner/striped/common dolphins) Subfamily Orcininae (melon-headed whales, false/pygmy killer whale, killer whale, pilot whales) Subfamily Stenoninae (rough-toothed/humpback dolphins) Genus *Lissodelphis* (right whale dolphins) *Lagenorhynchus albirostris* (white-beaked dolphin) *Lagenorhynchus acutus* (atlantic white-sided dolphin) *Lagenorhynchus obliquidens* (Pacific white-sided dolphin) *Lagenorhynchus obscurus* (dusky dolphin)
HF	High-frequency cetaceans	Family Phocoenidae (porpoises) Family Platanistidae (Indus/Ganges river dolphins) Family Iniidae (Amazon river dolphins) Family Pontoporiidae (Baiji/ La Plata river dolphins) Family Kogiidae (Pygmy/dwarf sperm whales) Genus *Cephalorhynchus* (Commersen's, Chilean, Heaviside's, Hector's dolphins) *Lagenorhynchus australis* (Peale's or black-chinned dolphin) *Lagenorhynchus cruciger* (hourglass dolphin)
PW	Phocids (water)	Family Phocidae (true seals)
OW	Otariids and other non-phocid marine carnivores (water)	Family Otariidae (eared seals and sea lions) Family Odobenidae (walrus) *Enhydra lutris* (sea otter) *Ursus maritimus* (polar bear)

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5. COMPOSITE AUDIOGRAMS

Composite audiograms for each species group were determined by first searching the available literature for threshold data for the species of interest. For each group, all available AEP and psychophysical (behavioral) threshold data were initially examined. To derive the composite audiograms, the following rules were applied:

1. For marine mammal species groups with three or more behavioral audiograms (all groups except low-frequency cetaceans), only behavioral (no AEP) data were used. Mammalian AEP thresholds are typically elevated from behavioral thresholds in a frequency-dependent manner, with increasing discrepancy between AEP and behavioral thresholds at the lower frequencies where there is a loss of phase synchrony in the neurological responses and a concomitant increase in measured AEP thresholds. The frequency-dependent relationship between the AEP and behavioral data is problematic for defining the audiogram slope at low frequencies. As a result of this rule, behavioral data were used for all groups. For all species groups, AEP threshold data were still used for interpreting the hearing ability of various species and determining the group to which they should belong.

   For the low-frequency cetaceans, for which no behavioral or AEP threshold data exist, predicted thresholds from mathematical models were used. The models are primarily based on measurements of basilar membrane dimensions obtained from computerized tomography (CT) scans of cetacean ears (e.g., Ketten and Mountain, 2014) or finite element models of head-related and middle-ear transfer functions derived from whole-head CT scans (e.g., Cranford and Krysl, 2015).

2. Data from an individual animal were included only once at a particular frequency. If data from the same individual were available from multiple studies, data at overlapping frequencies were averaged (this only occurred once, with threshold values differing by 8 dB). For the low-frequency cetaceans, if the same anatomical data were used in multiple mathematical models, the most recent predicted audiograms were used. For example, the humpback whale hearing model proposed by Ketten and Mountain (2014) not only featured the same ear specimens as Houser et al. (2001), but also utilized additional specimens acquired and analyzed since 2001. For this reason, the predicted audiogram from Houser et al. (2001) was not used to develop the composite audiogram, but the Ketten and Mountain (2014) predicted audiogram was.

3. Individuals with obvious high-frequency hearing loss for their species or aberrant audiograms (e.g., obvious notches or thresholds known to be elevated for that species due to masking or hearing loss) were excluded.

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4. Linear interpolation was performed within the threshold data for each individual to estimate a threshold value at each unique frequency present in any of the data for that species group. This was necessary to calculate descriptive statistics at each frequency without excluding data from any individual subject.

5. Composite audiograms were determined using both the original threshold values from each individual (in dB re 1 µPa) and normalized thresholds obtained by subtracting the lowest threshold value for that subject. For the low-frequency cetaceans, only normalized thresholds were used, since absolute threshold values are not generated directly from the anatomical data, but are obtained by estimating the threshold at the frequency of best hearing based on ambient noise data and/or thresholds for other species.

Table 2 lists the individual references for the data ultimately used to construct the composite audiograms. From these data, the median (50th percentile) threshold value was calculated at each frequency and fit by the function

$$T(f) = T_0 + A\log_{10}\left(1+\frac{F_1}{f}\right)+\left(\frac{f}{F_2}\right)^B, \quad (3)$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are fitting parameters. The median value was used to reduce the influence of outliers. The particular form of Eq. (3) was chosen to provide linear-log rolloff with variable slope at low frequencies and a steep rise at high frequencies. The form is similar to that used by Popov et al. (2007) to describe dolphin audiograms; the primary difference between the two is the inclusion of two frequency parameters in Eq. (3), which allows a more shallow slope in the region of best sensitivity. Equation (3) was fit to the median threshold data using nonlinear regression (National Instruments LabVIEW 2014). The resulting fitting parameters and goodness of fit values (R^2) are provided in Tables 3 and 4 for the original and normalized data, respectively. Figures 5 and 6 show the original and normalized threshold data, respectively, as well as the composite audiograms based on the fitted curve. The composite audiograms for each species group are compared in Fig. 6. To allow comparison with other audiograms based on the original threshold data, the lowest threshold for the low-frequency cetaceans was estimated to be 65 dB re 1 µPa. This was based on the range of 60 to 70 dB re 1 µPa estimated by Clark and Ellison (2004) and a comparison with historical ambient noise curves (National Research Council (NRC), 2003). From the composite audiograms, the frequency of lowest threshold, f_0, and the slope at the lower frequencies, s_0, were calculated (Table 5). Slopes were calculated across a frequency range of one decade, beginning with the lowest frequency present for each group.

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484 **Table 2.** References, species, and individual subjects used to derive the composite audiograms.

Group	Reference	Species	Subjects
LF	(Ketten and Mountain, 2014)	*Megaptera novaeangliae*	Predicted
	(Ketten, 2014)	*Balaenoptera acusorostrata*	Predicted
	(Ketten, 2014)	*Balaenoptera musculus*	Predicted
	(Cranford and Krysl, 2015)	*Balaenoptera physalus*	Predicted
MF	(Finneran et al., 2005b)	*Delphinapterus leucas*	Beethoven
	(Szymanski et al., 1999)	*Ocinus orca*	Yaka, Vigga
	(Nachtigall et al., 1995)	*Grampus griseus*	N/a
	(Kastelein et al., 2003)	*Stenella coeruleoalba*	Meyen
	(Lemonds, 1999)	*Tursiops truncatus*	Itsi Bitsy
	(Brill et al., 2001)	*Tursiops truncatus*	CAS
	(Ljungblad et al., 1982)	*Tursiops truncatus*	12-y male
	(Johnson, 1967)	*Tursiops truncatus*	Salty
	(Sauerland and Dehnhardt, 1998)	*Sotalia fluviatilis*	Paco
	(Johnson et al., 1989)	*Delphinapterus leucas*	2-y female
	(White et al., 1978)	*Delphinapterus leucas*	Edwina, Kojak
	(Awbrey et al., 1988)	*Delphinapterus leucas*	Kojak, female, male
	(Thomas et al., 1988)	*Pseudorca crassidens*	I'a nui hahai
	(Finneran et al., 2010a)	*Tursiops truncatus*	TYH
	(Schlundt et al., 2008)	*Tursiops truncatus*	WEN
	(Ridgway et al., 2001)	*Delphinapterus leucas*	MUK, NOC
	(Tremel et al., 1998)	*Lagenorhynchus obliquidens*	female
HF	(Jacobs and Hall, 1972)	*Inia geoffrensis*	male
	(Kastelein et al., 2002b)	*Phocoena phocoena*	PpSH047
	(Kastelein et al., 2010)	*Phocoena phocoena*	Jerry
OW	(Moore and Schusterman, 1987)	*Callorhinus ursinus*	Lori, Tobe
	(Babushina et al., 1991)	*Callorhinus ursinus*	N/a
	(Kastelein et al., 2002a)	*Odobenus rosmarus*	Igor
	(Mulsow et al., 2012)	*Zalophus californianus*	JFN
	(Reichmuth and Southall, 2012)	*Zalophus californianus*	Rio, Sam
	(Reichmuth et al., 2013)	*Zalophus californianus*	Ronan
	(Kastelein et al., 2005)	*Eumetopias jubatus*	EjZH021, EjZH022
	(Ghoul and Reichmuth, 2014)	*Enhydra lutris nereis*	Charlie
PW	(Kastak and Schusterman, 1999)	*Mirounga angustirostris*	Burnyce
	(Terhune, 1988)	*Phoca vitulina*	N/a
	(Møhl, 1968)	*Phoca vitulina*	3-4 y male
	(Terhune and Ronald, 1972)	*Pagophilus groenlandicus*	4-y female
	(Terhune and Ronald, 1975)	*Pusa hispida*	male, female
	(Reichmuth et al., 2013)	*Phoca vitulina*	Sprouts
	(Kastelein et al., 2009)	*Phoca vitulina*	01, 02
	(Sills et al., 2014)	*Phoca largha*	Amak, Tunu
	(Babushina, 1997)	*Pusa caspica*	N/a

15

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485

486 **Table 3.** Best-fit parameters for Eq. (3) fit to the original threshold data. Low-frequency cetaceans were
487 excluded since absolute thresholds are typically estimated by setting the lowest threshold to a particular
488 value based on ambient noise levels and/or other species thresholds.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	–	–	–	–	–	–
MF	49.8	20.6	57.7	35.4	4.37	0.977
HF	43.3	8.97	137	43.2	26.3	0.969
OW	63.4	2.87	12.2	30.4	3.34	0.944
PW	20.4	9510	4.58	12.7	1.46	0.925

489

490

491 **Table 4.** Best-fit parameters for Eq. (3) fit to the normalized threshold data.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	-2.67	0.594	3.11	35.9	1.84	0.992
MF	3.06	14.0	65.7	31.4	4.87	0.971
HF	0.258	21.8	132	36.1	21.0	0.959
OW	2.39	0.364	13.3	73.7	3.55	0.955
PW	-46.6	4820	3.69	16.4	1.38	0.941

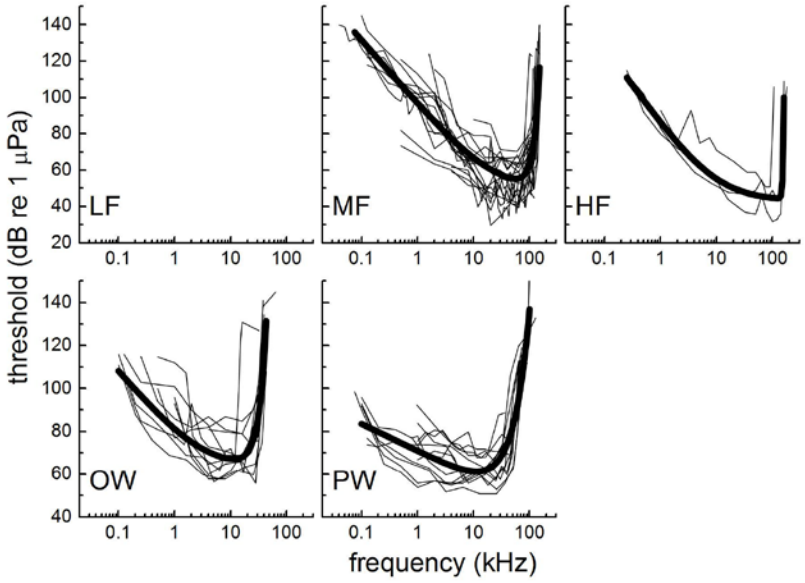
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494

495 **Figure 5.** Thresholds and composite audiograms for the five species groups. Thin lines represent the
496 threshold data from individual animals. Thick lines represent the best fit of Eq. (3). Thresholds are
497 expressed in dB re 1 µPa.

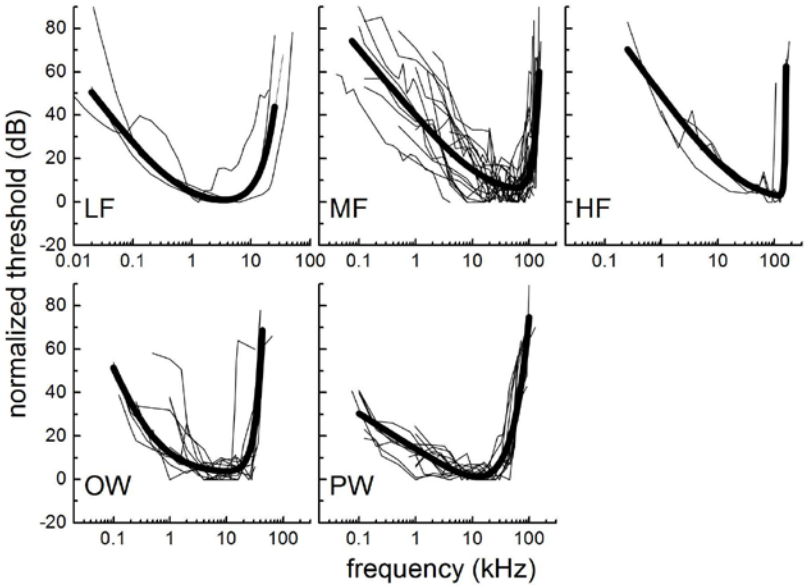
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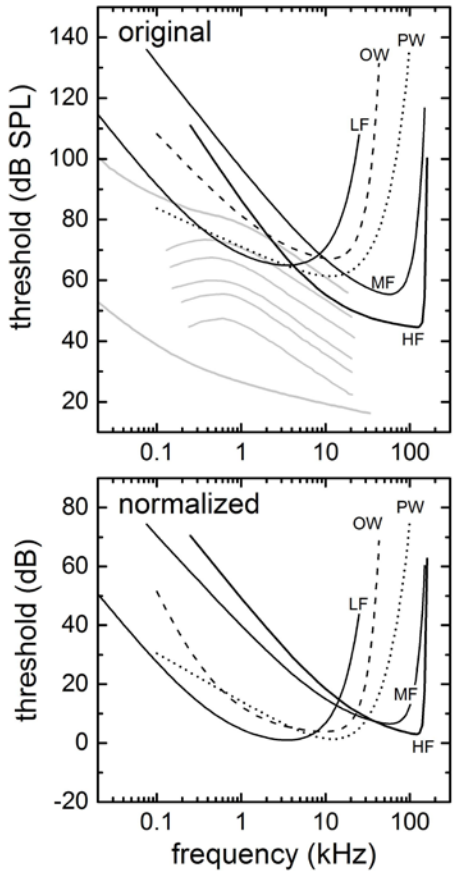
501 **Figure 6.** Normalized thresholds and composite audiograms for the five species groups. Thin lines
502 represent the threshold data from individual animals. Thick lines represent the best fit of Eq. (3).
503 Thresholds were normalized by subtracting the lowest threshold for each individual data set (i.e., within-
504 subject). Composite audiograms were then derived from the individually normalized thresholds (i.e., the
505 composite audiograms were not normalized and may have a minimum value ≠ 0).

506

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507

508 **Figure 7.** Composite audiograms for the various species groups, derived with the original data (upper)
509 and normalized data (lower). Thresholds in upper panels are expressed in dB re 1 µPa. The low-frequency
510 cetacean audiogram in the upper panel was estimated from the composite audiogram based on the
511 normalized data by setting the lowest threshold to 65 dB re 1 µPa (see Clark and Ellison, 2004). The gray
512 lines in the upper left panel represent ambient noise spectral density levels (referenced to the left
513 ordinate, in dB re 1 μPa^2/Hz) corresponding to the limits of prevailing noise and various sea-state
514 conditions, from 0 to 6 (National Research Council (NRC), 2003).

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515 **Table 5.** Frequency of best hearing (f_0) and the magnitude of the low-frequency slope (s_0) derived from
516 composite audiograms and equal latency contours. Audiogram slopes were calculated across a frequency
517 range of one decade, beginning with the lowest frequency present for each group. Equal latency slopes
518 were calculated from the available equal latency contours (Fig. 8).

Group	Original data composite audiogram		Normalized data composite audiogram		Equal latency curves
	f_0 (kHz)	s_0 (dB/decade)	f_0 (kHz)	s_0 (dB/decade)	s_0 (dB/decade)
LF	—	—	3.5	32	—
MF	58	35	58	31	31
HF	120	38	120	34	50
OW	12	27	10	39	—
PW	11	13	13	16	—

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6. EQUAL LOUDNESS DATA

Finneran and Schlundt (2011) conducted a subjective loudness comparison task with a bottlenose dolphin and used the resulting data to derive equal loudness contours and auditory weighting functions. The weighting functions agreed closely with dolphin TTS data over the frequency range 3 to 56 kHz (Finneran and Schlundt, 2013); however, the loudness data only exist for frequencies between 2.5 kHz and 113 kHz and cannot be used to estimate the shapes of loudness contours and weighting functions at lower frequencies.

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7. EQUAL LATENCY DATA

Reaction times to acoustic tones have been measured in several marine mammal species and used to derive equal latency contours and weighting functions (Fig. 8, Wensveen et al., 2014; Mulsow et al., 2015). Unlike the dolphin equal loudness data, the latency data extend to frequencies below 1 kHz and may be used to estimate the slopes of auditory weighting functions at lower frequencies.

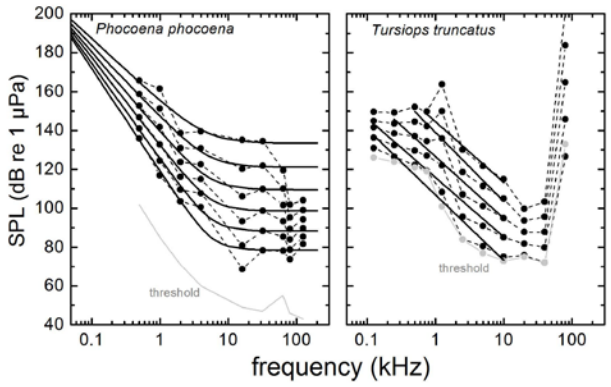


Figure 8. Underwater marine mammal equal latency contours are available for *Phocoena phocoena* (Wensveen et al., 2014) and *Tursiops truncatus* (Mulsow et al., 2015). The slopes for the contours at low frequencies were obtained from the literature (*Phocoena phocoena*) or calculated from the best linear-log fits to the lower frequency data. The slope of the contour passing through an SPL approximately 40 dB above the threshold at f_0 was selected as the most appropriate based on: (1) human A-weighting, (2) observations that the relationship between equal latency and loudness can break down at higher sensation levels, and (3) for many data sets the slopes increase at higher SPLs rather than decrease as expected. The resulting slopes are listed in Table 5.

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8. TTS DATA

8.1. Non-impulsive (steady-state) exposures - TTS

For weighting function derivation, the most critical data required are TTS onset exposure levels as a function of exposure frequency. These values can be estimated from published literature by examining TTS as a function of SEL for various frequencies.

To estimate TTS onset values, only TTS data from psychophysical (behavioral) hearing tests were used. Studies have shown differences between the amount of TTS from behavioral threshold measurements and that determined using AEP thresholds (Fig. 9). TTS determined from AEP thresholds is typically larger than that determined behaviorally, and AEP-measured TTS of up to ~ 10 dB has been observed with no corresponding change in behavioral thresholds (e.g., Finneran et al., 2007). Although these data suggest that AEP amplitudes and thresholds provide more sensitive indicators (than behavioral thresholds) of the auditory effects of noise, Navy acoustic impact analyses use TTS both as an indicator of the disruption of behavioral patterns that are mediated by the sense of hearing and to predict when the onset of PTS is likely to occur. Navy analyses assume that exposures resulting in a NITS > 40 dB measured a few minutes after exposure will result in some amount of residual PTS. This is based on relationships observed in early human TTS studies utilizing psychophysical threshold measurements. To date, there have been no reports of PTS in a marine mammal whose initial behavioral threshold shift was 40 dB or less; however, behavioral shifts of 35 to 40 dB have required multiple days to recover, suggesting that these exposures are near those capable of resulting in PTS. In contrast, studies utilizing AEP measurements in marine mammals have reported TTSs of 45 dB that recovered in 40 min and 60 dB that recovered in < 24 h, suggesting that these exposures were not near those capable of resulting in PTS (Popov et al., 2013).

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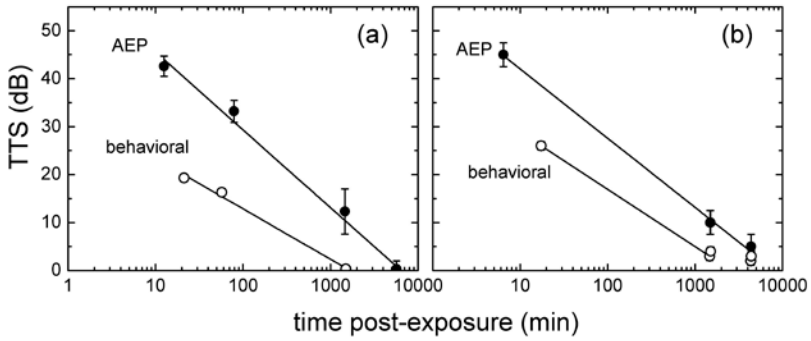


Figure 9. TTS measured using behavioral and AEP methods do not necessarily agree, with marine mammal studies reporting larger TTS obtained using AEP methods. For the data above, thresholds were determined using both techniques before and after the same noise exposure. Hearing thresholds were measured at 30 kHz. Behavioral thresholds utilized FM tones with 10% bandwidth. AEP thresholds were based on AM tones with a modulation frequency of 1.05 kHz. Noise exposures consisted of (a) a single, 20-kHz tone with duration of 64 s and SPL of 185 dB re 1 µPa (SEL = 203 dB re 1 $\mu Pa^2 s$) and (b) three 16-s tones at 20 kHz, with mean SPL = 193 dB re 1 µPa (cumulative SEL = 210 dB re 1 $\mu Pa^2 s$). Data from Finneran et al. (2007).

To determine TTS onset for each subject, the amount of TTS observed after exposures with different SPLs and durations were combined to create a single TTS growth curve as a function of SEL. The use of (cumulative) SEL is a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles. This is referred to as an "equal energy" approach, since SEL is related to the energy of the sound and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound. It is well-known that the equal energy rule will over-estimate the effects of intermittent noise, since the quiet periods between noise exposures will allow some recovery of hearing compared to noise that is continuously present with the same total SEL (Ward, 1997). For continuous exposures with the same SEL but different durations, the exposure with the longer duration will also tend to produce more TTS (e.g., Kastak et al., 2007; Mooney et al., 2009; Finneran et al., 2010a). Despite these limitations, however, the equal energy rule is still a useful concept, since it includes the effects of both noise amplitude and duration when predicting auditory effects. SEL is a simple metric, allows the effects of multiple noise sources to be combined in a meaningful way, has physical significance, and is correlated with most TTS growth data reasonably well — in some cases even across relatively large ranges of exposure duration (e.g., Popov et al., 2014). The use of cumulative SEL for Navy sources will always over-estimate the effects of intermittent or interrupted sources, and the majority of Navy sources feature durations shorter than the exposure durations typically utilized in marine

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mammal TTS studies, therefore the use of (cumulative) SEL will tend to over-estimate the effects of many Navy sound sources.

Marine mammal studies have shown that the amount of TTS increases with SEL in an accelerating fashion: At low exposure SELs, the amount of TTS is small and the growth curves have shallow slopes. At higher SELs, the growth curves become steeper and approach linear relationships with the noise SEL. Accordingly, TTS growth data were fit with the function

$$t(L) = m_1 \log_{10}\left[1+10^{(L-m_2)/10}\right], \quad (4)$$

where t is the amount of TTS, L is the SEL, and m_1 and m_2 are fitting parameters. This particular function has an increasing slope when $L < m_2$ and approaches a linear relationship for $L > m_2$ (Maslen, 1981). The linear portion of the curve has a slope of $m_1/10$ and an x-intercept of m_2. After fitting Eq. (4) to the TTS growth data, interpolation was used to estimate the SEL necessary to induce 6 dB of TTS — defined as the "onset of TTS" for Navy acoustic impact analyses. The value of 6 dB has been historically used to distinguish non-trivial amounts of TTS from fluctuations in threshold measurements that typically occur across test sessions. Extrapolation was not performed when estimating TTS onset; this means only data sets with exposures producing TTS both above and below 6 dB were used.

Figures 10 to 13 show all behavioral and AEP TTS data to which growth curves defined by Eq. (4) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Table 6.

8.2. Non-impulsive (steady-state) exposures - PTS

Since no studies have been designed to intentionally induce PTS in marine mammals (but see Kastak et al., 2008), onset-PTS levels for marine mammals must be estimated. Differences in auditory structures and sound propagation and interaction with tissues prevent direct application of numerical thresholds for PTS in terrestrial mammals to marine mammals; however, the inner ears of marine and terrestrial mammals are analogous and certain relationships are expected to hold for both groups. Experiments with marine mammals have revealed similarities between marine and terrestrial mammals with respect to features such as TTS, age-related hearing loss, ototoxic drug-induced hearing loss, masking, and frequency selectivity (Nachtigall et al., 2000; Finneran et al., 2005b; Finneran, 2012). For this reason, relationships between TTS and PTS from marine and terrestrial mammals can be used, along with TTS onset values for marine mammals, to estimate exposures likely to produce PTS in marine mammals (Southall et al., 2007).

A variety of terrestrial and marine mammal data sources (e.g., Ward et al., 1958; Ward et al., 1959; Ward, 1960; Miller et al., 1963; Kryter et al., 1966) indicate that threshold shifts up to 40 to 50 dB may be induced without PTS, and that 40 dB is a conservative upper limit for threshold shift to prevent PTS; i.e., for impact analysis, 40 dB of NITS is an upper limit for reversibility and that any additional exposure will result in some PTS.

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This means that 40 dB of TTS essentially defines the onset of PTS and an exposure causing 40 dB of TTS is equivalent to PTS onset.

Therefore, to estimate PTS onset, TTS growth curves based on more than 20 dB of measured TTS were extrapolated to determine the SEL required for a TTS of 40 dB. The SEL difference between TTS onset and PTS onset was then calculated. The requirement that the maximum amount of TTS must be at least 20 dB was made to avoid over-estimating PTS onset by using growth curves based on small amounts of TTS, where the growth rates are shallower than at higher amounts of TTS.

8.3. Impulsive exposures

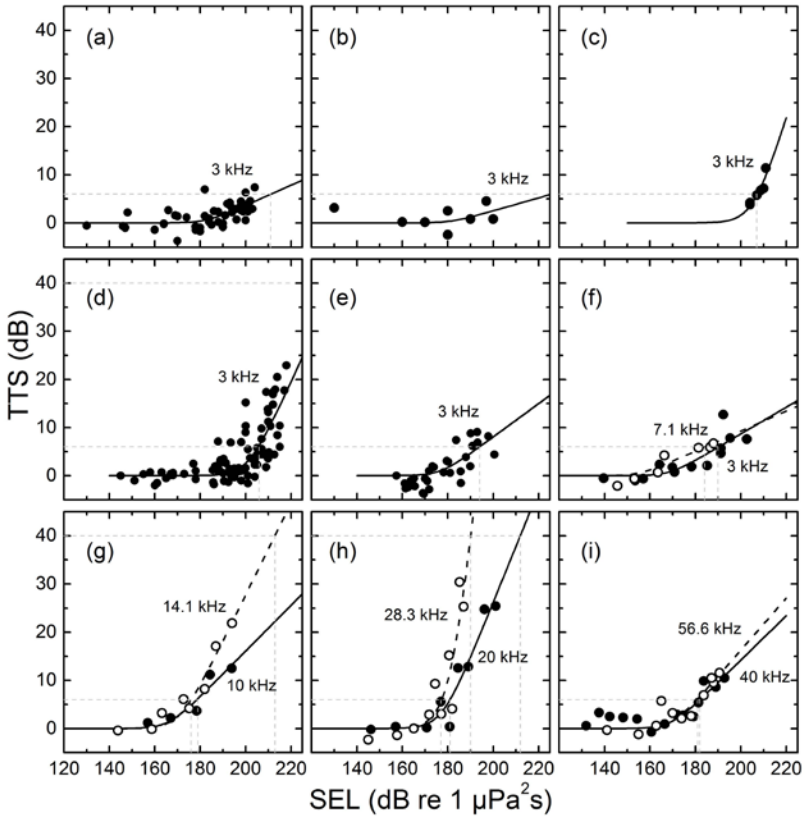
Marine mammal TTS data from impulsive sources are limited to two studies with measured TTS of 6 dB or more: Finneran et al. (2002) reported behaviorally-measured TTSs of 6 and 7 dB in a beluga exposed to single impulses from a seismic water gun (unweighted SEL = 186 dB re 1 μPa^2s, peak SPL = 224 dB re 1 µPa) and Lucke et al. (2009) reported AEP-measured TTS of 7 to 20 dB in a harbor porpoise exposed to single impulses from a seismic air gun [Fig. 12(f), TTS onset = unweighted SEL of 162 dB re 1 μPa^2s or peak SPL of 195 dB re 1 µPa]. The small reported amounts of TTS and/or the limited distribution of exposures prevent these data from being used to estimate PTS onset.

In addition to these data, Kastelein et al. (2015b) reported behaviorally-measured mean TTS of 4 dB at 8 kHz and 2 dB at 4 kHz after a harbor porpoise was exposed to a series of impulsive sounds produced by broadcasting underwater recordings of impact pile driving strikes through underwater sound projectors. The exposure contained 2760 individual impulses presented at an interval of 1.3 s (total exposure time was 1 h). The average single-strike, unweighted SEL was approximately 146 dB re 1 μPa^2s and the cumulative (unweighted) SEL was approximately 180 dB re 1 μPa^2s. The pressure waveforms for the simulated pile strikes exhibited significant "ringing" not present in the original recordings and most of the energy in the broadcasts was between 500 and 800 Hz, near the resonance of the underwater sound projector used to broadcast the signal. As a result, some questions exist regarding whether the fatiguing signals were representative of underwater pressure signatures from impact pile driving.

Several impulsive noise exposure studies have also been conducted without measurable (behavioral) TTS. Finneran et al. (2000) exposed dolphins and belugas to single impulses from an "explosion simulator" (maximum unweighted SEL = 179 dB re 1 μPa^2s, peak SPL = 217 dB re 1 µPa) and Finneran et al. (2015) exposed three dolphins to sequences of 10 impulses from a seismic air gun (maximum unweighted cumulative SEL = 193 to 195 dB re 1 μPa^2s, peak SPL =196 to 210 dB re 1 µPa) without measurable TTS. Finneran et al. (2003) exposed two sea lions to single impulses from an arc-gap transducer with no measurable TTS (maximum unweighted SEL = 163 dB re 1 μPa^2s, peak SPL = 183 dB re 1 µPa).

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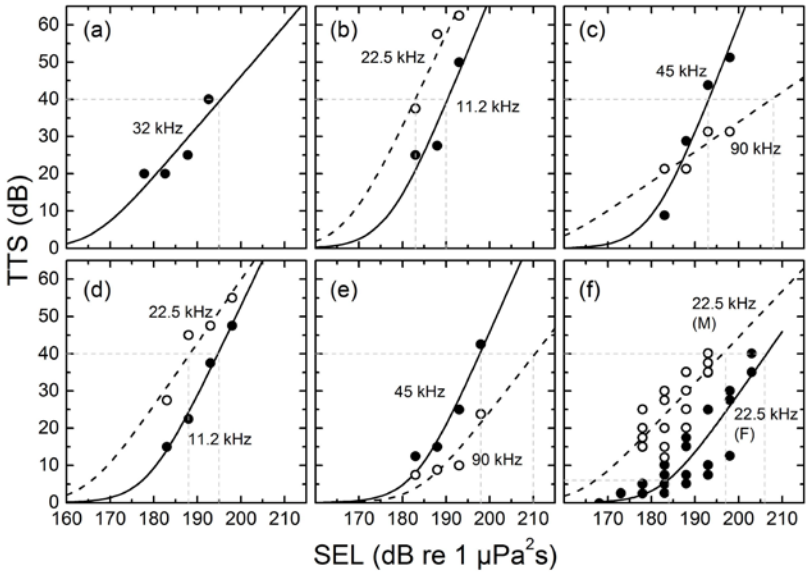
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679 **Figure 10.** TTS growth data for mid-frequency cetaceans obtained using behavioral methods. Growth
680 curves were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the
681 SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset
682 PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with
683 maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines
684 are fit to the filled symbols; dashed lines are fit to the open symbols. See Table 6 for explanation of the
685 datasets in each panel. Frequencies listed in each panel denote the exposure frequency.

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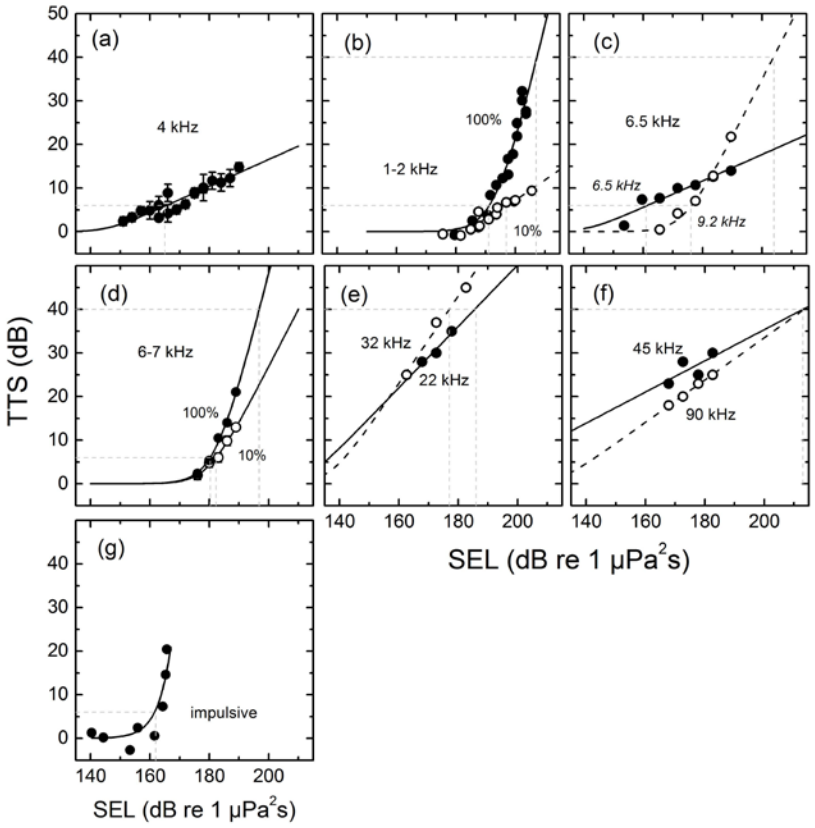
688 **Figure 11.** TTS growth data for mid-frequency cetaceans obtained using AEP methods. Growth curves
689 were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL
690 value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS
691 was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum
692 TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to
693 the filled symbols; dashed lines are fit to the open symbols. See Table 6 for explanation of the datasets in
694 each panel.

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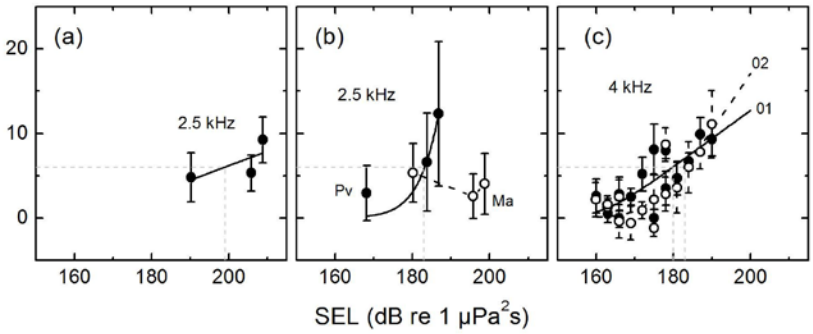
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698 **Figure 12.** TTS growth data for high-frequency cetaceans obtained using behavioral and AEP methods.
699 Growth curves were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined
700 as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS.
701 Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with
702 maximum TTS > 20 dB. The exposure frequency is specified in normal font; italics indicate the hearing test
703 frequency. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table 6 for
704 explanation of the datasets in each panel.

705

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707 **Figure 13.** TTS growth data for pinnipeds obtained using behavioral methods. Growth curves were
708 obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value
709 from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Frequency values
710 within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines
711 are fit to the open symbols. See Table 6 for explanation of the datasets in each panel.

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Table 6. Summary of marine mammal TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 $\mu Pa^2 s$. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements unless otherwise indicated.

Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
MF	*Tursiops truncatus*	BEN	3	0	7	211*	0.21	—	—	TTS onset higher than subsequent test	(Finneran et al., 2005a)	10(a)
MF	*Tursiops truncatus*	NAY	3	0	5	—	0.13	—	—		(Finneran et al., 2005a)	10(b)
MF	*Tursiops truncatus*	BLU	3	4	11	207*	1.5	—	—	intermittent	(Finneran et al., 2010b)	10(c)
MF	*Tursiops truncatus*	BLU	3	0	23	206*	1.0	240	34	TTS onset higher than subsequent tests	(Finneran et al., 2010a)	10(d)
MF	*Tursiops truncatus*	TYH	3	0	9	194	0.35	—	—		(Finneran et al., 2010a)	10(e)
MF	*Tursiops truncatus*	BLU	3 7.1 10 14.1 20 28.3	0 0 1 0 0 0	13 7 13 22 25 30	190 184 179 176 181 177	0.28 0.21 0.48 0.95 1.2 4.5	— — — 213 212 190	— — — 37 31 13		(Finneran and Schlundt, 2013)	10(f) 10(f) 10(g) 10(g) 10(h) 10(h)
MF	*Tursiops truncatus*	TYH	40 56.6	0 0	11 12	182 181	0.46 1.1	— —	— —		(Finneran and Schlundt, 2013)	10(i) 10(i)
MF	*Delphinapterus leucas*	N/a	32	20	40	—	1.4	195	—	AEP	(Popov et al., 2011b)	11(a)

Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
MF	*Delphinapterus leucas*	female	11.2 22.5 45 90	25 38 9 21	50 63 51 31	— — — —	2.8 2.5 3.0 0.8	190 183 193 208	— — — —	AEP	(Popov et al., 2013)	11(b) 11(b) 11(c) 11(c)
MF	*Delphinapterus leucas*	male	11.2 22.5 45 90	15 28 13 8	48 55 42 24	— — — —	2.5 1.7 2.7 1.5	195 188 198 210	— — — —	AEP	(Popov et al., 2013)	11(d) 11(d) 11(e) 11(e)
MF	*Delphinapterus leucas*	female	22.5	0	40	184*	1.7	206	22	AEP	(Popov et al., 2014)	11(f)
MF	*Delphinapterus leucas*	male	22.5	12	40	—	1.2	197	—	AEP	(Popov et al., 2014)	11(f)
HF	*Phocoena phocoena*	02	4	2	15	165	0.3	—	—		(Kastelein et al., 2012a)	12(a)
HF	*Phocoena phocoena*	02	~1.5 ~1.5	0 0	32 7	191 197*	2.8 0.4	207 —	16 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2014b)	12(b) 12(b)
HF	*Phocoena phocoena*	02	6.5 6.5	1 0	13 22	161 176*	0.3 1.3	— 204	— 28	6.5 kHz test freq. 9.2 kHz test freq.	(Kastelein et al., 2014a)	12(c) 12(c)
HF	*Phocoena phocoena*	02	~6.5 ~6.5	2 2	21 13	180* 182*	2.7 1.3	197 —	17 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2015a)	12(d) 12(d)
HF	*Neophocaena phocaenoides*	male	22 32	28 25	35 45	— —	0.7 1.0	186 177	— —	AEP	(Popov et al., 2011a)	12(e)
HF	*Neophocaena phocaenoides*	female	45 90	23 18	30 25	— —	0.36 0.48	213 213	— —	AEP	(Popov et al., 2011a)	12(f)
HF	*Phocoena phocoena*	Eigil	impulse	0	20	162	**	—	—	AEP	(Lucke et al., 2009)	12(g)

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Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
OW	*Zalophus californianus*	Rio	2.5	5	9	199	0.17	—	—		(Kastak et al., 2005)	13(a)
PW	*Phoca vitulina*	Sprouts	2.5	3	12	183	6.4	—	—		(Kastak et al., 2005)	13(b)
PW	*Mirounga angustirostris*	Burnyce	2.5	3	5	—	—	—	—		(Kastak et al., 2005)	13(b)
PW	*Phoca vitulina*	01	4	0	10	180	0.33	—	—		(Kastelein et al., 2012b)	13(c)
PW	*Phoca vitulina*	02	4	0	11	183*	0.68	—	—	TTS_{16}	(Kastelein et al., 2012b)	13(c)

718 * SELs not used in subsequent analyses to optimize ΔT or define K for TTS or PTS exposure functions. Reasons for exclusion include: (i) another data set resulted in a lower
719 onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) data
720 were obtained from AEP testing, or (v) a lower TTS onset was found at a different hearing test frequency (also see Notes).

721 ** Distribution of data did not support an accurate estimate for growth rate (the standard error was four orders of magnitude larger than the slope estimate)

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9. TTS EXPOSURE FUNCTIONS FOR SONARS

Derivation of the weighting function parameters utilized the exposure function form described by Eq. (2), so that the shapes of the functions could be directly compared to the TTS onset data (Table 6) when available. The function shapes were first determined via the parameters a, b, f_1, and f_2, then the gain constant K was determined for each group to provide the best fit to the TTS data or estimated TTS onset value at a particular frequency.

9.1. Low- and high-frequency exponents (a, b)

The high-frequency exponent, b, was fixed at $b = 2$. This was done to match the previous value used in the Phase 2 functions, since no new TTS data are available at the higher frequencies and the equal latency data are highly variable at the higher frequencies.

The low-frequency exponent, a, was defined as $a = s_0/20$, where s_0 is the lower of the slope of the audiogram or equal latency curves (in dB/decade) at low frequencies (Table 5), for all groups except the low-frequency cetaceans (see below). This causes the weighting function slope to match the shallower slope of the audiogram or equal latency contours at low frequencies. In practice, the audiogram slopes were lower than the equal latency slopes for all groups except the mid-frequency cetaceans (group MF). Given the uncertainties in the predicted audiograms for the low-frequency cetaceans, a slope of 30 dB/decade — based on the slopes of low-frequency ambient noise curves (see Fig. 7) — was used instead of the predicted audiogram slope (32 dB/decade).

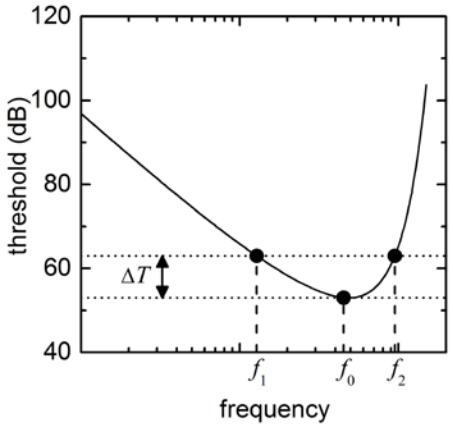
9.2. Frequency cutoffs (f_1, f_2)

The frequency cutoffs f_1 and f_2 were defined as the frequencies below and above the frequency of best hearing (f_0, Table 5) where the composite audiogram thresholds values were ΔT-dB above the threshold at f_0 (Fig. 14).

To determine ΔT, the exposure function amplitude defined by Eq. (2) was calculated for the mid- and high-frequency cetaceans using ΔT values that varied from 0 to 20 dB. For each ΔT value, the constant K was adjusted to minimize the mean-squared error between the function amplitude and the TTS data (Fig. 15). This process was performed using composite audiograms based on both the original and normalized threshold data. Fits were performed using only TTS data resulting from continuous exposures (100% duty cycle). If hearing was tested at multiple frequencies after exposure, the lowest TTS onset value was used.

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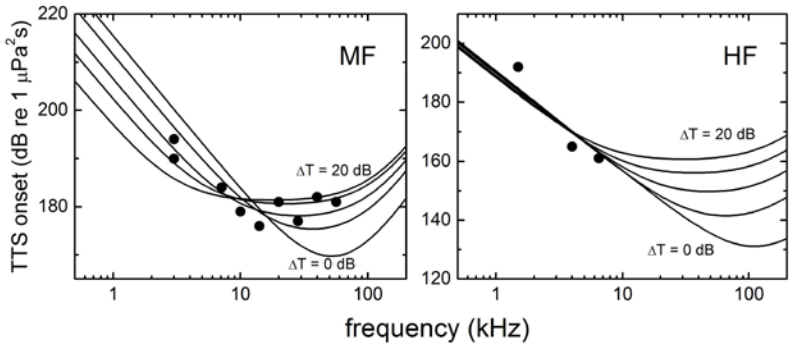
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759

760 **Figure 14.** The cutoff frequencies f_1 and f_2 were defined as the frequencies below and above f_0 at which
761 the composite audiogram values were ΔT-dB above the threshold at f_0 (the lowest threshold).

762



763

764 **Figure 15.** Effect of ΔT adjustment on the TTS exposure functions for the mid-frequency cetaceans (left)
765 and high-frequency cetaceans (right). To calculate the exposure functions, a and b were defined as a =
766 $s_0/20$ and b = 2. ΔT was then varied from 0 to 20. At each value of ΔT, K was adjusted to minimize the
767 squared error between the exposure function and the onset TTS data (symbols). As ΔT increases, f_1
768 decreases and f_2 increases, causing the pass-band of the function to increase and the function to "flatten".

769

770 For the original and normalized data, the errors between the best-fit exposure functions and
771 the TTS data for the MF and HF cetaceans were squared, summed, and divided by the total
772 number of TTS data points (12). This provided an overall mean-squared error (MSE) for the

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original and normalized data as a function of ΔT (Fig. 16). The conditions (ΔT value and original/normalized threshold audiograms) resulting in the lowest MSE indicated the best fit of the exposure functions to the TTS data. For the MF and HF cetacean data, the lowest MSE occurred with the normalized threshold data with $\Delta T = 11$ dB. **Therefore, f_1 and f_2 for the remaining species groups were defined using composite audiograms based on normalized thresholds with $\Delta T = 11$ dB.**

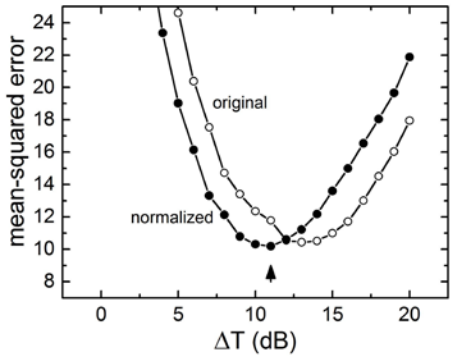


Figure 16. Relationship between ΔT and the resulting mean-squared error (MSE) between the exposure functions and onset TTS data. The MSE was calculated by adding the squared errors between the exposure functions and TTS data for the MF and HF cetacean groups, then dividing by the total number of TTS data points. This process was performed using the composite audiograms based on original and normalized threshold data and ΔT values from 0 to 20. The lowest MSE value was obtained using the audiograms based on normalized thresholds with $\Delta T = 11$ dB (arrow).

9.3. Gain parameters *K* and *C*

The gain parameter K was defined to minimize the squared error between the exposure function and the TTS data for each species group.

For the low-frequency cetaceans, for which no TTS data exist, TTS onset at the frequency of best hearing (f_0) was estimated by assuming that, at the frequency of best hearing, the numeric difference between the auditory threshold (in dB SPL) and the onset of TTS (in dB SEL) would be similar to that observed in the other species groups. Table 7 summarizes the onset TTS and composite threshold data for the MF, HF, OW, and PW groups. Because the HF difference (108) was considerably lower than the others (125, 133, 121), and this group shares the least in common with the mysticetes in terms of audible frequency range and best sensitivity, the median value (123) was used rather than the mean (122). The best threshold for the LF group was estimated at 65 dB re 1 µPa, based on a range of 60 to 70 dB re 1 µPa estimated by Clark and Ellison (2004) and a comparison with historical ambient noise curves (National Research Council (NRC),

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2003). The TTS onset value at the estimated frequency of best hearing sensitivity is therefore 188 dB re 1 μPa^2s for the low-frequency cetaceans (Table 7).

Table 7. Differences between (normalized) composite threshold values and TTS onset values at the frequency of best hearing (f_0) for marine mammal species groups. The value for the low-frequency cetaceans was estimated using the median difference (123) from the other groups.

Group	f_0 (kHz)	Threshold at f_0 (dB re 1 µPa)	TTS onset at f_0 (dB re 1 μPa^2s)	Difference	Estimated difference	Estimated TTS onset at f_0 (dB re 1 μPa^2s)
LF	3.5	65			123	188
MF	58	55	180	125		
HF	120	45	153	108		
OW	12	67	200	133		
PW	11	61	182	121		

The constant C was determined by substituting parameters a, b, f_1, and f_2 into Eq. (1), then adjusting C so the maximum amplitude of the weighting function was 0 dB. Finally, the weighted threshold for onset TTS was determined from the minimum value of the exposure function; this is mathematically equivalent to $K + C$.

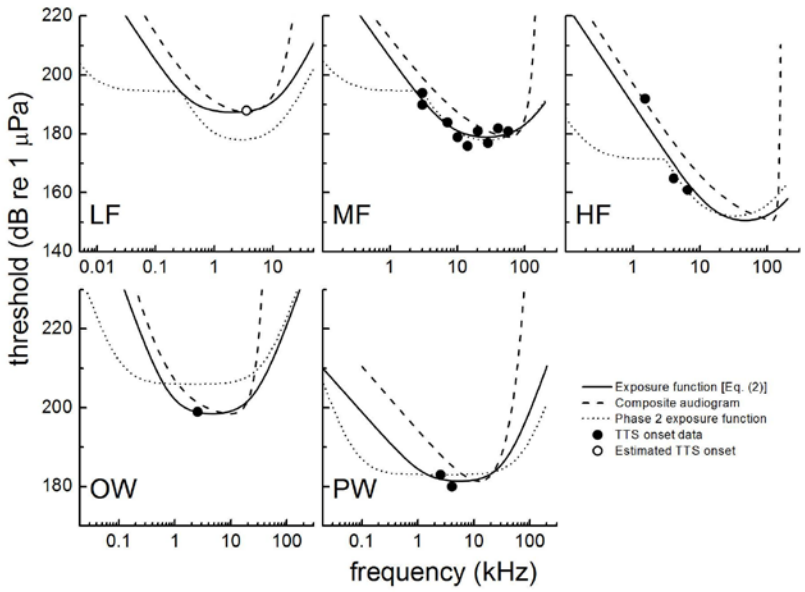
Table 8 summarizes the various function parameters, the weighted TTS thresholds, and the goodness of fit values between the TTS exposure functions and the onset TTS data. The various TTS exposure functions are presented in Figs. 17–20.

Table 8. Weighting function and TTS exposure function parameters for use in Eqs. (1) and (2) for steady-state exposures. R^2 values represent goodness of fit between exposure function and TTS onset data (Table 6).

Group	a	b	f_1 (kHz)	f_2 (kHz)	K (dB)	C (dB)	Weighted TTS threshold (dB SEL)	R^2
LF	1.5	2	0.38	13	187	0.43	187	—
MF	1.6	2	7.4	110	178	1.02	179	0.845
HF	1.7	2	16	150	149	1.63	151	0.851
OW	2	2	0.77	27	198	0.49	198	—
PW	0.8	2	1.3	37	181	0.38	181	0.261

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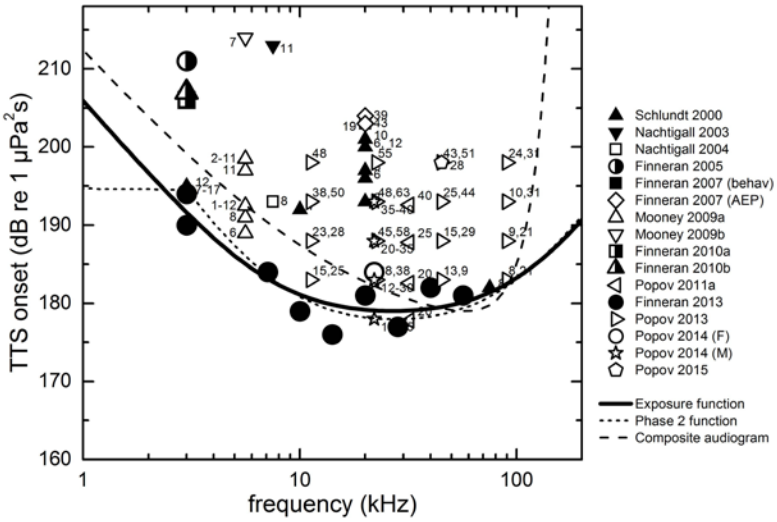
820 **Figure 17.** Exposure functions (solid lines) generated from Eq. (2) with the parameters specified in Table
821 7. Dashed lines — (normalized) composite audiograms used for definition of parameters a, f_1, and f_2. A
822 constant value was added to each audiogram to equate the minimum audiogram value with the exposure
823 function minimum. Short dashed line — Navy Phase 2 exposure functions for TTS onset for each group.
824 Filled symbols — onset TTS exposure data (in dB SEL) used to define exposure function shape and vertical
825 position. Open symbols — estimated TTS onset for species for which no TTS data exist.

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828 **Figure 18.** Mid-frequency cetacean exposure function, (normalized) composite audiogram, and Phase 2
829 exposure functions compared to mid-frequency cetacean TTS data. Large symbols with no numeric values
830 indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric
831 values giving the amount (or range) or measured TTS. Filled and half-filled symbols — behavioral data.
832 Open symbols — AEP data.

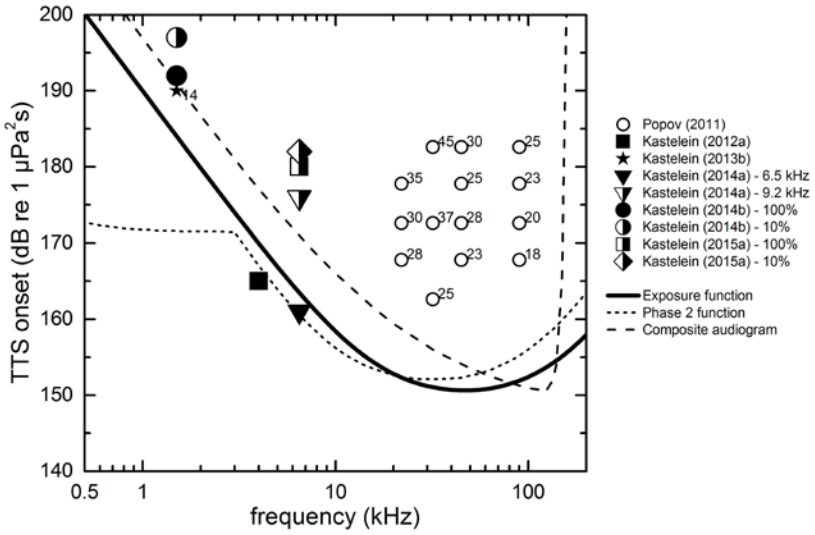
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835 **Figure 19.** High-frequency cetacean TTS exposure function, (normalized) composite audiogram, and
836 Phase 2 exposure functions compared to high-frequency cetacean TTS data. Large symbols with no
837 numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS
838 observed, with numeric values giving the amount (or range) or measured TTS. Filled and half-filled
839 symbols — behavioral data. Open symbols — AEP data.

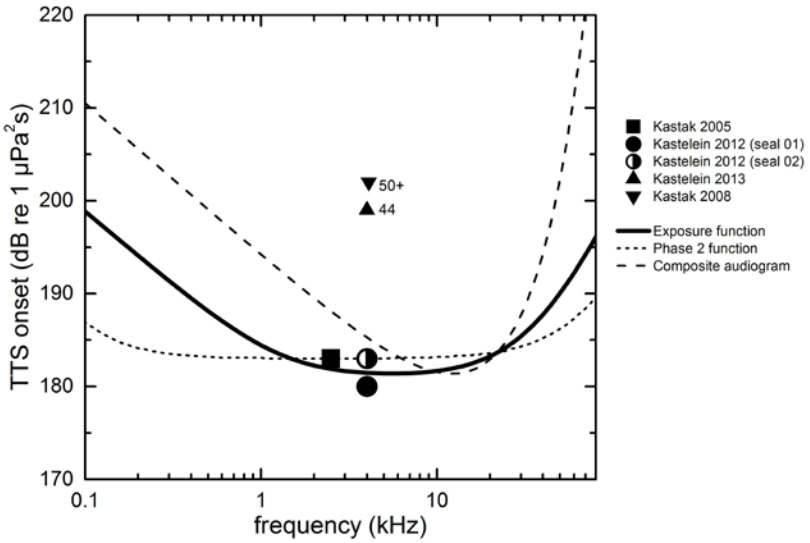
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842

843 **Figure 20.** Phocid exposure function, (normalized) composite audiogram, and Phase 2 exposure
844 functions compared to phocid TTS data. Large symbols with no numeric values indicate onset TTS
845 exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the
846 amount (or range) or measured TTS.

847

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10. PTS EXPOSURE FUNCTIONS FOR SONARS

As in previous acoustic effects analyses (Southall et al., 2007; Finneran and Jenkins, 2012), the shape of the PTS exposure function for each species group is assumed to be identical to the TTS exposure function for that group. Thus, definition of the PTS function only requires the value for the constant K to be determined. This equates to identifying the increase in noise exposure between the onset of PTS and the onset of TTS.

For Phase 2, Navy used a 20-dB difference between TTS onset and PTS onset for cetaceans and a 14-dB difference for phocids, otariids, odobenids, mustelids, and ursids (Finneran and Jenkins, 2012). The 20-dB value was based on human data (Ward et al., 1958) and the available marine mammal data, essentially following the extrapolation process proposed by Southall et al. (2007). The 14-dB value was based on a 2.5 dB/dB growth rate reported by Kastak et al. (2007) for a California sea lion tested in air.

For Phase 3, a difference of 20 dB between TTS onset and PTS onset is used for all species groups. This is based on estimates of exposure levels actually required for PTS (i.e., 40 dB of TTS) from the marine mammal TTS growth curves (Table 6), which show differences of 13 to 37 dB (mean = 25, median = 28, n = 7) between TTS onset and PTS onset in marine mammals. These data show most differences between TTS onset and PTS onset are larger than 20 dB and all but one value are larger than 14 dB.

The value of K for each PTS exposure function and the weighted PTS threshold are therefore determined by adding 20 dB to the K-value for the TTS exposure function or the TTS weighted threshold, respectively (see Table 10).

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11. TTS/PTS EXPOSURE FUNCTIONS FOR EXPLOSIVES

The shapes of the TTS and PTS exposure functions for explosives and other impulsive sources are identical to those used for sonars and other active acoustic sources (i.e., steady-state or non-impulsive noise sources). Thus, defining the TTS and PTS functions only requires the values for the constant K to be determined. This equates to identifying the weighted exposures necessary for TTS and PTS.

Phase 3 analyses for TTS and PTS from underwater detonations and other impulsive sources follow the approach proposed by Southall et al. (2007) and used in Phase 2 analyses (Finneran and Jenkins, 2012), where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold. The threshold producing the greater range for effect is then used because it is the more protective of the dual thresholds.

Peak SPL and SEL thresholds for TTS were based on TTS data from impulsive sound exposures that produced 6 dB or more TTS for the mid- and high-frequency cetaceans (the only groups for which data are available). The peak SPL thresholds were taken directly from the literature: 224 and 196 dB re 1 µPa, for the mid- and high-frequency cetaceans, respectively (Table 9). The SEL-based thresholds were determined by applying the Phase 3 weighting functions for the appropriate species groups to the exposure waveforms that produced TTS, then calculating the resulting weighted SELs. When this method is applied to the exposure data from Finneran et al. (2002) and Lucke et al. (2009), the SEL-based weighted TTS thresholds are 172 and 139 dB re 1 μPa^2s for the mid- and high-frequency cetaceans, respectively (Table 9). Note that the data from Lucke et al. (2009) are based on AEP measurements and may thus under-estimate TTS onset; however, they are used here because of the very limited nature of the impulse TTS data for marine mammals and the likelihood that the high-frequency cetaceans are more susceptible than the mid-frequency cetaceans (i.e., use of the mid-frequency cetacean value is not appropriate). Based on the limited available data, it also seems reasonable to assume that the exposures described by Lucke et al. (2009), which produced AEP-measured TTS of up to 20 dB, would have resulted in a behavioral TTS of at least 6 dB.

The harbor porpoise data from Kastelein et al. (2015b) were not used to derive the high-frequency cetacean TTS threshold, since the largest observed TTS was only 4 dB. However, these data provide an opportunity to check the TTS onset proposed for the HF cetacean group. Kastelein et al. (2015b) provide a representative frequency spectrum for a single, simulated pile driving strike at a specific measurement location. When the HF cetacean weighting function is applied to this spectrum and the 1/3-octave SELs combined across frequency, the total weighted SEL for a single strike is found to be 112 dB re 1 μPa^2s. For 2760 impulses, the cumulative, weighted SEL would then be 146 dB re 1 μPa^2s. The average SEL in the pool was reported to be 9 dB lower than the SEL at the measurement position, thus the average, cumulative weighted SEL would be approximately 137 dB re 1 μPa^2s, which compares favorably to the HF cetacean TTS threshold of 139 dB re 1 μPa^2s derived from the Lucke et al. (2009) air gun data.

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For species groups for which no impulse TTS data exist, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the mid- and high-frequency cetaceans:

$$G_s - G_i = \overline{C_s} - \overline{C_i}, \quad (5)$$

where G indicates thresholds for a species group for which impulse TTS data are not available, $\overline{C}$ indicates the mean of the mid- and high-frequency cetacean thresholds, the subscript s indicates a steady-state threshold, and the subscript i indicates an impulse threshold. Equation (5) is equivalent to the relationship used by Southall et al. (2007), who expressed the relationship as $\overline{C_s} - G_s = \overline{C_i} - G_i$. For the mid- and high-frequency cetaceans, the steady-state TTS thresholds are 179 and 151 dB re 1 μPa^2s, respectively, and the impulse TTS thresholds are 172 and 139 dB re 1 μPa^2s, respectively, making $\overline{C_s} - \overline{C_i}$ = 10 dB. Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 10 dB below the steady-state TTS threshold (Table 9).

To estimate peak SPL-based thresholds, Southall et al. (2007) used Eq. (5) with peak-SPL values for the impulse thresholds and SEL-based values for the steady-state thresholds. For the mid- and high-frequency cetaceans, the steady-state (SEL) TTS thresholds are 179 and 151 dB re 1 μPa^2s, respectively, and the peak SPL, impulse TTS thresholds are 224 and 196 dB re 1 µPa, respectively, making $\overline{C_s} - \overline{C_i}$ = -45 dB. Based on this relationship, the peak SPL-based impulse TTS threshold (in dB re 1 µPa) would be 45 dB above the steady-state TTS threshold (in dB re 1 μPa^2s), making the peak SPL thresholds vary from 227 to 246 dB re 1 µPa. Given the limited nature of the underlying data, and the relatively high values for some of these predictions, for Phase 3 analyses Navy uses the mid-frequency cetacean peak SPL threshold (224 dB re 1 µPa) for the other underwater groups (Table 9).

Since marine mammal PTS data from impulsive noise exposures do not exist, onset-PTS levels for these animals were estimated by adding 15 dB to the SEL-based TTS threshold and adding 6 dB to the peak pressure based thresholds. These relationships were derived by Southall et al. (2007) from impulse noise TTS growth rates in chinchillas. The appropriate frequency weighting function for each functional hearing group is applied only when using the SEL-based thresholds to predict PTS.

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940 **Table 9.** TTS and PTS thresholds for explosives and other impulsive sources. SEL thresholds are in dB re 1
941 $\mu Pa^2 s$. Peak SPL thresholds are in dB re 1 µPa .

Group	TTS threshold		PTS threshold	
	SEL (weighted) (dB SEL)	peak SPL (dB SPL)	SEL (weighted) (dB SEL)	peak SPL (dB SPL)
LF	177	224	192	230
MF	172	224	187	230
HF	139	196	154	202
OW	188	224	203	230
PW	171	224	186	230

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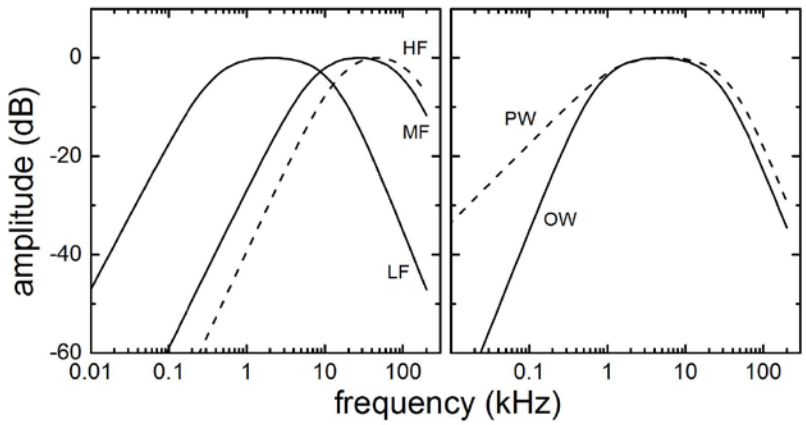
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943 **12. SUMMARY**

944 Figure 21 illustrates the shapes of the various Phase 3 auditory weighting functions.
945 Table 10 summarizes the parameters necessary to calculate the weighting function
946 amplitudes using Eq. (1).

947



948

949 **Figure 21.** Navy Phase 3 weighting functions for cetaceans and marine carnivores.
950 Parameters required to generate the functions are provided in Table 10.

951

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Table 10. Summary of weighting function parameters and TTS/PTS thresholds. SEL thresholds are in dB re 1 µPa^{2}s. Peak SPL thresholds are in dB re 1 µPa.

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$$

						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1.5	2	0.38	13	0.43	187	207	177	224	192	230
MF	1.6	2	7.4	110	1.02	179	199	172	224	187	230
HF	1.7	2	16	150	1.63	151	171	139	196	154	202
OW	2	2	0.77	27	0.49	198	218	188	224	203	230
PW	0.8	2	1.3	37	0.38	181	201	171	224	186	230

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958 To properly compare the TTS/PTS criteria and thresholds used by Navy for Phase 2 and
959 Phase 3, both the weighting function shape and weighted threshold values must be taken
960 into account; the weighted thresholds by themselves only indicate the TTS/PTS threshold
961 at the most susceptible frequency (based on the relevant weighting function). Since the
962 exposure functions incorporate both the shape of the weighting function and the weighted
963 threshold value, they provide the best means of comparing the frequency-dependent
964 TTS/PTS thresholds for Phase 2 and 3 (Figs 22 and 23).

965 The most significant differences between the Phase 2 and Phase 3 functions include the
966 following:

967 (1) Thresholds at low frequencies are higher for Phase 3 compared to Phase 2. This is
968 because the Phase 2 weighting functions utilized the "M-weighting" functions (Southall
969 et al., 2007) at lower frequencies, where no TTS existed at that time. Since derivation of
970 the Phase 2 thresholds, additional data have been collected (e.g., Kastelein et al., 2012a;
971 Kastelein et al., 2013b; Kastelein et al., 2014b) to support the use of exposure functions
972 that continue to increase at frequencies below the region of best sensitivity, similar to the
973 behavior of mammalian audiograms and human auditory weighting functions.

974 (2) The LF cetacean thresholds are higher at all frequencies compared to those used in
975 Phase 2. In Phase 2, LF cetaceans were assumed to have TTS thresholds at their most
976 susceptible frequency equal to those of MF cetaceans at their most susceptible frequency.
977 However, LF cetaceans have best sensitivity at lower frequencies than MF cetaceans. For
978 LF cetaceans, hearing sensitivity at low frequencies is likely limited by historical ocean
979 noise levels (Clark and Ellison, 2004), and it is doubtful that LF cetaceans would possess
980 thresholds as low as those seen in MF cetaceans. Therefore, the TTS/PTS thresholds for
981 LF cetaceans were increased relative to those used in Phase 2.

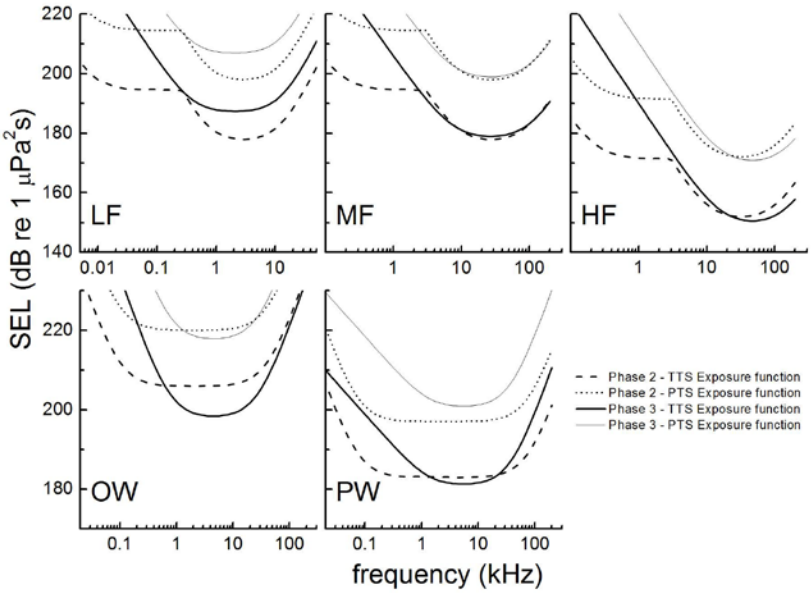
982 (3) The Phase 3 underwater thresholds for otariids and other marine carnivores (group
983 OW) are lower than those used in Phase 2. In Phase 2, the TTS onset for the otariids was
984 taken directly from the published literature (Kastak et al., 2005); for Phase 3, the actual
985 TTS data from Kastak et al. (2005) were fit by a TTS growth curve using identical
986 methods as those used with the other species groups.

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988

989 **Figure 22.** TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources.
990 Heavy solid lines — Navy Phase 3 TTS exposure functions (Table 10). Thin solid lines — Navy Phase 3 PTS
991 exposure functions for TTS (Table 10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed
992 lines — Navy Phase 2 PTS exposure functions.

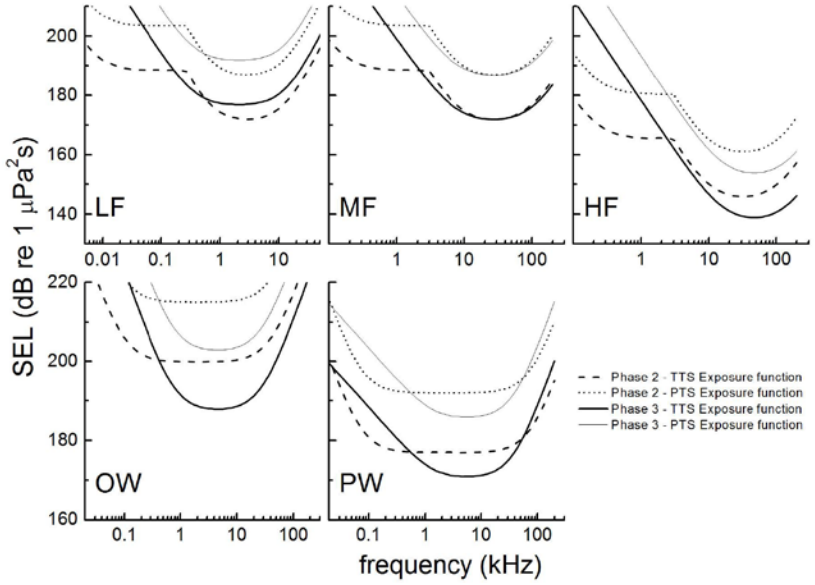
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995

996 **Figure 23.** TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other
997 impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table 10). Thin solid lines —
998 Navy Phase 3 PTS exposure functions for TTS (Table 10). Dashed lines — Navy Phase 2 TTS exposure
999 functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

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APPENDIX B: ANALYSIS TO SUPPORT RECOMMENDED TRANSITION FROM IMPULSIVE TO NON-IMPULSIVE ACOUSTIC THRESHOLD LEVELS

I. INTRODUCTION

This appendix provides the analysis (field measurements and marine mammal TTS data) used to support the Guidance's recommendation that action proponents be able to transition to using a non-impulsive PTS onset acoustic threshold level if the impulsive PTS onset acoustic threshold results in a predicted isopleth for auditory injury greater than 3 km.

NOAA acknowledges that numerous factors contribute to impulsive sounds being particularly injurious (e.g., number of impulses and repetition rate; Henderson and Hamernik 1986). Nevertheless, we have decided to focus on peak pressure and pulse duration (as a surrogate for rise time) as these consistently change with range from the source.

1.1 PEAK PRESSURE LEVELS

Typically, most sound source measurements (i.e., sound source verifications) are taken to examine at what distance various isopleths occur based on specific acoustic threshold levels. It is not often that measurements are reported (or data is provided) depicting how the waveform of a sound changes with distance from the source. However, several studies have collected information showing reductions in peak pressure with increasing distance from the sources producing impulsive sounds. These studies are reviewed below for high explosives, seismic airguns, and impact pile drivers.

1.1.1 Underwater High Explosives

High explosives produce shock waves, with fast rise times (i.e., microseconds) and high pressures followed by a sequence of bubble pulses, with each subsequent bubble having a lower pressure than the previous (i.e., second bubble has a peak pressure of only one fifth of the first bubble). At further ranges from the source, the pressure signatures of explosions are affected by refraction and multipath propagation, especially the high-frequency components of these sound (Urick 1983; Cudahy and Parvin 2001).

It should be noted that in addition to acoustic threshold levels associated with auditory impacts, underwater explosives have acoustic threshold levels associated with non-auditory impacts (e.g., lung injury; NOAA 2013b). Furthermore, the peak pressure PTS onset acoustic threshold levels, which is part of this Guidance's dual acoustic threshold levels, is most likely to be the dominant acoustic threshold level (i.e., producing the largest isopleth) for a source, like high explosives. Additionally, shock wave predictions and actual measurements indicate for explosives that peak pressure scales with range and charge weight

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(i.e., R/ $W^{1/3}$), as well as provides information on time decay, which could be used to better support an alternative transition range for explosives

Compared to high explosives, airguns and impact pile drivers have lower peak pressures and longer rise times (e.g., Hill 1978; Cudahy and Parvin 2001; Ruggerone et al. 2008; Caltrans 2012).

1.1.2 Seismic Airguns

Several examples of seismic airgun measurements showing decreases in pressure, over time and space (i.e., via waveform), include:

- Greene and Richardson 1988: Measurements of various marine seismic survey sounds (i.e., sleeve exploders, open bottom gas guns, single airguns and airgun arrays) in the Beaufort Sea (water depth 9 to 130 m, but mostly less than 50 m), from various distances, were provided. In general, they concluded, "Pulses received at ranges greater than 3-4 km were usually 0.25-0.75 s long." Examples are provided in Figures 2 and 7 of their publication.

- Wardle et al. 2001: Measurements were taken at different distances (16 to 206 m) from an airgun array (three synchronized 150 in^3 airguns) in Loch Ewe, Scotland (water depth 10 to 20 m), with relative pressure amplitudes depicted in Figure 4 from their publication. For example, the initial peak pressure amplitude drops from 206 dB at 16 m from the source to 190 dB at 206 m from the source, with the largest drop in amplitude occurring within the first 50 m of propagation.

- Breitzke et al. 2008: Calibration measurements of an airgun array (~518 in^3) were made in Herdlefjord, Norway (water depth ~200 to ~380 m). Figure 8 from their publication compares peak pressure levels at distances of 564 m and 1571 m from the source, where there is a decrease in peak pressure in the farthest measurements (180 dB_{peak} versus <170 dB_{peak}).

- Blees et al. 2010: Sound source verification measurements for a mitigation airgun (60 in^3) and full array (3000 in^3) were made in the Chukchi Sea (water depth 38 to 43 m). Figure 3.7 of their report shows how the peak pressure decreases from ~ 200 dB at 460 m from the source to ~186 dB at 1.953 km from the source for the full array. For the mitigation airgun, Figure 3.13 of their report illustrates how the peak pressure drops from ~186 dB at 50 m from the source to ~178 dB by 500 m from the source.

- Illingworth & Rodkin 2014: A VSP (750 in^3) measurement was conducted in Cook Inlet, Alaska (water depth 15 m). In Figure 11 of their report, there is a decrease in peak pressure from measurements 175 m (~189 dB_{peak}; pulse duration ~0.03 s) from source compared to 1,089 m (<180 dB_{peak}; pulse duration ~0.115 s) from source, as

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well as a change in the waveform, including an increase in pulse duration. The distance to the 160 dB behavioral threshold was predicted at 3,800 m.

1.1.3 Impact Pile Drivers

Several examples of impact pile driving measurements showing decreases in pressure, over time and space (i.e., via waveform), include:

- Nedwell et al. 2003: Measurements associated with the installation of the North Hoyle windfarm (pile diameter 4 m) off northern Wales (Liverpool Bay; water depth 7-11 m) were reported. Figures 18 through 20 of their report illustrates how peak pressure levels change with distance from the source (i.e., ~192 dB 955 m from source, ~186 dB 1881 m from the source, and ~178 dB 3905 m from source).

- Blackwell et al. 2004a: Measurements associated with the installation of 51-cm well conductor and 107-cm diameter well insulator pipes, associated with the construction of the Northstar Island facility in Prudhoe Bay, Alaska (water depth 6 m), were reported at distances 63 to 1000 m from the source. From Figure 4 of their publication, for the 51-cm pipe at 1000 m from the source, the peak pressure had dropped by over 30 dB (i.e., at 63 m peak pressure is 157 dB, while at 1000 m it is less than 130 dB). For the 107-cm pipe, at 200 m from the source, the peak pressure was ~155 dB, while at 1000 m from the source; it had dropped to ~140 dB. Pulse durations for these measurements varied from 0.11 to 0.6 s.

- Bailey et al. 2010: Measurements of pile driving sounds associated with the installation of a windfarm (pile diameter 1.8 m tubular steel) off northeast Scotland at distances of 100 m up to 60 km from the operation (water depth 42 m) were reported. Figure 3 from their publication illustrates how the peak pressure levels change with distance from the source, especially from measurements at 100 m (~197 dB) versus at 1,520 m (~180 dB). This paper predicted auditory injury (i.e., PTS acoustic threshold levels for both pinnipeds and cetaceans from Southall et al. 2007) to occur within 100 m of the pile.

- Zampolli et al. 2013: Measurements associated with an 18-inch steel pile in Kinderdijk, The Netherlands; water depth 7 m). Figure 2 from this publication illustrates the waveform associated with measurements 5 and 68 m from the pile. Despite measurements taken at close ranges, the peak sound pressure level dropped from ~210 dB at 5 m to ~197 dB at 68 m.

- Illingworth & Rodkin 2014: Measurements associated with impact pile driving for a conductor pipe (30 in) was conducted in Cook Inlet, Alaska (water depth 15 m). In Figure 14 of their report, there is a significant drop in peak pressure from measurements 55 m (~ 186 dB_{peak}; pulse duration ~0.045 s) from source compared to 1,150 m (~166 dB_{peak}; pulse duration ~0.084 s) from source, as well as a change in

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the waveform, including an increase in pulse duration. The distance to the 160 dB behavioral threshold was predicted at 1,630 m.

In addition to the examples above, Caltrans (2012) provides a summary of impact pile driving measurements. Despite most measurements occurring at close ranges to the source, this document does provide some information how peak pressure levels decrease up to 1000 m from the source (Table B1).

Table B1: Summary of impact pile driving measurements at various distances from the source (Caltrans 2012).

Pile Type (size)	Project	Project Location (water depth)	Distance from Pile	Peak Sound Pressure Level
CISS steel pipe (96-in)	Benicia-Martinez Bridge	Benicia, California (3-7 m)	5 m	227 dB
			10m	220 dB
			20 m	214 dB
			50 m	210 dB
			100 m	204 dB
			500 m	188 dB
			1000 m	180 dB
CISS steel pipe (96-in)	SFOBB Skyway Construction	Oakland, California (5-8 m)	50 m	185-190 dB
			100 m	185-205 dB
			500 m	170-185 dB
			1000 m	160-170 dB
CISS steel pipe (150 & 166 in)	Richmond-San Rafael Bridge	San Rafael, California (>15 m)	20 m	208-215 dB
			50 m	205 dB
			95 m	194 dB
			160 m	191 dB
			235 m	192 dB
			~1000 m	169 dB
Steel pipe (30-in)	SR 520 Test pile project	Seattle, Washington (3-7 m)	10 m	196 dB
			200 m	177 dB
			500 m	160 dB

CISS: cast-in-steel-shell
SFOBB: San Francisco-Oakland Bay Bridge

1.2 PULSE DURATION AND RISE TIME

Another factor that makes impulsive sounds particularly injurious is their fast rise time. However, for most sources in the field, rise time is difficult to measure and/or not typically reported. Thus, the Guidance uses total pulse duration as a surrogate for rise time duration because as a sound propagates through the environment, pulse duration is expected to increase, resulting in a subsequent decrease in rise time (i.e., slower rise times). NOAA

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acknowledges this assumption that may not always reflect the physics of propagation (e.g., Breitzke et al. 2008 illustrates that rise time is similar between measurements at 564 and 1571 m from the source. Nevertheless, there is over a 10 dB reduction in peak pressure at 1571 m from the source, which is why NOAA is considering both pulse duration and peak pressure). Nevertheless, NOAA considers this the best approach based on available data.

Furthermore, NOAA acknowledges that multipath propagation[29], which is dependent on range (R) from the source, as well as water depth (H), is an important factor contributing to pulse duration (i.e., more multipath arrivals in shallower water and with higher R/H ratio; Harrison and Nielsen 2007; Harrison 2011; Ainslie et al. 2014). The R/H ratio can be an additional factor for consideration to determine the appropriateness of the proposed transition range (i.e., with increasing range from the source this ratio increases).

Additionally, rapid rise times are often tied to the high-frequency content of impulsive sounds (e.g., explosives, sonic booms, and firearms; Henderson and Hamernik 1986). Furthermore, terrestrial mammal studies indicate that impulse sounds with higher frequency components result in increasing susceptibility to noise-induced hearing loss compared to those with primarily lower frequency content (Walker and Behar 1971; Price 1983; Price et al. 1989; Hamernik et al. 1991). For example, Price (1983) examined the effects of two different impulsive sources (rifle and cannon) on threshold shifts in cats. With exposure to equal peak pressures, threshold shifts began at a lower exposure level for the rifle, which had a faster A duration (time from initial pressure rise to first zero crossing) and subsequent higher frequency content (i.e., spectral peak for cannon was three octaves higher, related to rise time) than that of the cannon. Additionally, terrestrial mammals (Hamernik et al. 1991), as well as marine mammals, have demonstrated that higher frequencies typically have higher growth rates (Finneran and Schlundt 2013). Of course, it is important to consider this in light of the different marine mammal functional hearing groups (i.e., high and low frequency is relative to each particular functional hearing group). Nevertheless, as sound propagates through the environment, the high frequency content typically attenuate faster than low frequency content, which also potentially reduces the injurious nature of these types of sounds as a receiver gets further away.

1.2.1 Ratio of Peak Pressure to Pulse Duration

Finding an appropriate metric to determine at what ranges impulsive sounds begin to lose the characteristics that make them particularly injurious (i.e., high peak pressure and fast rise time), as well as having measurements for impulsive sounds in the field at various distance from the source, is challenging. NOAA considered previously defined metrics, such as kurtosis and crest factor. However, neither of these metrics are deemed useful for purposes of the Guidance (i.e., kurtosis is not a practical metric to measure and implement; crest factor did not provide a reliable indicator of a sounds decrease in impulsive characteristics

[29] Multipath propagation occurs whenever there is more than one propagation path between the source and receiver (i.e., direct path and paths from reflections off the surface and bottom or reflections within a surface or deep-ocean duct; Urick 1983).

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with distance, with the crest factor often remaining unchanged close to the source and up to 10+ km from the source).

Instead, NOAA explored using a simple ratio of peak pressure (Pascals) to pulse duration[30] to gauge how these physical characteristics changed with range from the source by compiling currently available datasets for high explosives, seismic airguns, and impact pile drivers (Table B2). Larger ratios (> 10,000) occur at ranges where there are higher peak pressures and shorter pulse durations. With propagation and increased distance from the source, peak pressures begin to diminish and pulse durations increase as a result of multipath propagation and reverberation (e.g., Richardson 2000; Blackwell et al. 2004; Madsen et al. 2006), resulting in progressively smaller ratios (≤ 10,000).

Table B2: Summary of impulsive sound datasets providing information on peak pressure and pulse duration at various distances from the source.

Source	Location (Water Depth)	Distance from Source	Peak Pressure*	Pulse Duration*	Ratio (Pa/s)	Reference
High Explosives						
Explosion simulator (5 kg charge)	Modeled based on data from Baltic Sea (24 m)	1.5 km	15849 Pa (204 dB)	0.0087 s	1,821,724	Finneran et al. 2000
		3.7 km	6025 Pa (195.6 dB)	0.013 s	463,462	
Explosion simulator (500 kg charge)	Modeled based on data from Baltic Sea (24 m)	1.7 km	70795 Pa (217 dB)	0.0095 s	7,452,105	Finneran et al. 2000
		1.9 km	56234 Pa (215 dB)	0.0051 s	11,026,275	
		3.7 km	26915 Pa (208.6 dB)	0.011 s	2,446,818	
Seismic Airguns						
Open bottom gas gun	Beaufort Sea, Alaska (9-11 m)	0.9 km	*1202 Pa (181.6 dB)*	0.2 s	6,010	Greene and Richardson 1988
Airgun (1709 in^3)		1.9 km	*1109 Pa (180.9 dB)*	0.2 s	5,545	
VSP (760 in^3)	Santa Barbara Channel, California (396 m)	0.07 km	*14125 Pa (203 dB)*	*0.005 s*	2,825,000	HESS 1999‡
		0.5 km	*2818 Pa (189 dB)*	*0.4 s*	7,045	
		1 km	*224 Pa (167 dB)*	*0.5 s*	448	

[30] Pulse duration is defined as the time interval between the arrival of 5% and 95% of total pulse energy.

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Airgun (1210 in^3)	Beaufort Sea, Alaska (23-26 m)	0.2 km	*4467 Pa (193 dB)*	*0.04 s*	111,675	Richardson 2000
		0.5 km	*3162 Pa (190 dB)*	*0.06 s*	52,700	
		1 km	*1000 Pa (180 dB)*	*0.1 s*	10,000	
		2 km	*562 Pa (175 dB)*	*0.15 s*	3,747	
		3 km	*316 Pa (170 dB)*	*0.2 s*	1,580	
Airgun (3147 in^3)	Chukchi Sea, Alaska (40 m)	0.35 km	*17783 Pa (205 dB)*	*0.07 s*	254,043	Patterson et al. 2007
		0.5 km	*10000 Pa (200 dB)*	*0.1 s*	100,000	
		1 km	*4467 Pa (193 dB)*	*0.2 s*	22,335	
		2 km	*1778 Pa (185 dB)*	*0.4 s*	4,445	
		3 km	*1000 Pa (180 dB)*	*0.5 s*	2,000	
Airgun (1049 in^3)		0.175 km	*25119 Pa (208 dB)*	*0.05 s*	502,380	
		0.275 km	*17783 Pa (205 dB)*	*0.1 s*	177,830	
		0.5 km	*10000Pa (200 dB)*	*0.17 s*	58,824	
		1 km^	*5623 Pa (195 dB)*	*0.2 s*	28,115	
Airgun (40 in^3)	Chukchi Sea, Alaska (41-48 m); Honeyguide site	0.3 km	*1000 Pa (180 dB)*	*0.1 s*	10,0000	Reiser et al. 2010
		0.5 km	*562 Pa (175 dB)*	*0.065 s*	8,646	
		1 km	*316 Pa (170 dB)*	*0.1 s*	3,160	
		2 km	*100 Pa (160 dB)*	*0.15 s*	667	
		3 km	*56 Pa (155 dB)*	*0.2 s*	280	
	Chukchi Sea, Alaska (41-48 m); Burger site	0.3 km	*3162 Pa (190 dB)*	*0.045 s*	70,267	
		0.5 km	*1413 Pa (183 dB)*	*0.04 s*	35,325	
		1 km	*562 Pa (175 dB)*	*0.05 s*	11,240	
		2 km	*316 Pa*	*0.08 s*	3,825	

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			(170 dB)			
		3 km	*178 Pa (165 dB)*	*0.1 s*	1,780	
Airgun (40 in^3)	Chukchi Sea, Alaska (37 m)	0.05 km	*7943 Pa (198 dB)*	*0.05 s*	158,860	Hartin et al. 2011
		0.1 km	*5623 Pa (195 dB)*	*0.03 s*	187,433	
		1 km	*794 Pa (178 dB)*	*0.1 s*	7,940	
		2 km	*316 Pa (170 dB)*	*0.2 s*	1,580	
		3 km	*126 Pa (162 dB)*	*0.25 s*	504	
Airgun (4380 in^3)	Beaufort Sea, Alaska (0.5-2 km)	1 km	*3162 Pa (190 dB)*	*0.15 s*	21,080	Beland et al. 2013
		2 km	*1778 Pa (185 dB)*	*0.2 s*	8,890	
		3 km	*1000 Pa (180 dB)*	*0.2 s*	5,000	
		4 km	*562 Pa (175 dB)*	*0.2 s*	2,810	
Airgun (70 in^3)	Beaufort Sea, Alaska (0.5-2 km)	0.5 km	*1000 Pa (180 dB)*	*0.15 s*	6,667	Beland et al. 2013
		1 km	*562 Pa (175 dB)*	*0.1 s*	5,620	
		2 km	*316 Pa (170 dB)*	*0.2 s*	1,580	
		3 km	*178 Pa (165 dB)*	*0.2 s*	890	
VSP (750 in^3)	Cook Inlet, Alaska (15 m)	0.175 km	*2818 Pa (189 dB)*	0.03 s	93,9333	Illingworth & Rodkin 2014
		1.089 km	*891 Pa (179 dB)*	0.115 s	7,748	
		2.461 km	*501 Pa (174 dB)*	0.128 s	3,914	
Impact Pile Drivers						
Windfarm construction (1.8 m steel pile)	Northeast Scotland (42 m)	0.1 km	*7079 Pa (197 dB)*	0.01 s^+	707,900	Bailey et al. 2010
		1.52 km	*1000 Pa (180 dB)*	0.08 s^+	12,500	
		4.55 km	*501 Pa (174 dB)*	0.2 s^+	2,505	
Dock modification (91 cm steel	Knik Arm, Alaska (10-17 m)	0.06 km	*17783 Pa (205 dB)*	0.1 s	177,830	Blackwell 2005†
		0.15 km	*14125 Pa*	*0.09 s*	156,944	

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pile)			*(203 dB)*			
		0.7 km	*3548 Pa (191 dB)*	*0.13 s*	27,292	
		1.1 km	*1778 Pa (185 dB)*	*0.06 s*	29,633	
		1.9 km	*1000 Pa (180 dB)*	*0.2 s*	5,000	
Conductor pipe (76 cm pipe)	Cook Inlet, Alaska (15 m)	0.055 km	*1995 Pa (186 dB)*	0.045 s	44,333	Illingworth & Rodkin 2014
		1.15 km	*200 Pa (166 dB)*	0.084 s	2,381	

* Peak pressure or pulse durations listed in italics indicates estimated from reference (i.e., opposed to precise value being directly provided). In this document, this metric is abbreviated dB_{peak}, which is equivalent to the ANSI abbreviation of L_{pk} (ANSI 2013).

‡ HESS 1999 provides additional upslope measurements, which demonstrate similar trends to downslope measurements depicted in this Table.

^ Data depicted in Table is for bow aspect measurements, which are typically louder than those measured at the stern aspect. However, for this study, measurements are not provided beyond 1 km. For stern aspect (for comparison), the ratios are the following: 1 km = 7,062; 2 km= 1,124; 3 km = 527.

+ Pulse duration from personal communication with Bailey (2015).

† Blackwell 2005 provides additional measurements for shallow-water hydrophone, which demonstrate similar trends to that of deep-water hydrophone depicted in this table. Measurements were not made beyond 1.9 km.

NOAA acknowledges that there are limited data sets available to evaluate fully the use of this ratio, with most measurements coming from shallow water. NOAA understands that this ratio can be affected by numerous factors, including source characteristics, including frequency, bathymetry, water depth, bottom sediment composition and can be highly variable especially close to the source. Nevertheless, the data available do demonstrate some consistent, general trends for most impulsive sounds (exception high explosives), where the ratio dramatically decreases by approximately 1 to 2 km from the source.

Note: NOAA is not asking or requiring action proponents to conduct measurements to determine when impulsive sources begin to lose those characteristics making them more injurious. However, NOAA acknowledges that additional measurements would help support this methodology or allow NOAA to explore methodology that is may be more appropriate.

1.2.1.1 How Peak Pressure to Pulse Duration Ratio Relates to Marine Mammal TTS Data

To determine an appropriate ratio, as to when impulsive sounds start to lose some of their more injurious characteristics, available data from marine mammal TTS studies for impulsive sounds were also examined (Table B3). NOAA acknowledges that the use of TTS data in

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this manner is not consistent with measurements from acoustic sources, since hearing measurements and exposures occur close to the source. Nevertheless, these data offer a means of comparison (i.e., comparison of ratio between TTS data and acoustic sources) and can provide insight on source characteristic associated with noise-induced hearing loss.

Table B3: Summary of marine mammal TTS studies using impulsive sounds.

Source	Species (n)	Measured TTS Frequencies‡	Peak Pressure	Pulse Duration	Ratio* (Pa/s)	Reference
Explosion simulator (500 kg charge)	Beluga (1); Bottlenose dolphin (2)	1.2, 1.8, and 2.4 kHz	69183 Pa (216.8 dB)	0.0095 s	7,282,421	Finneran et al. 2000
Water gun (80 in^3)	Beluga (1)	**0.4**, 4, and **30** kHz	158489 Pa (224 dB)	0.0063 s	**25,156,984**	Finneran et al. 2002
Water gun (80 in^3)	Bottlenose dolphin (1)	0.4, 4, and 30 kHz	218776 Pa (226.8 dB)	0.01 s	21,877,600	Finneran et al. 2002
Arc-gap transducer	California sea lion (2)	1 and 10 kHz	13963 Pa (202.9 dB)	0.0142	983,310	Finneran et al. 2003
Airgun (20 in^3)	Harbor porpoise	**4**, 32, and 100 kHz	5623 Pa (195 dB)	0.05 s+	**112,460**	Lucke et al. 2009
Impact pile driver (4.2 m pile at 800 m)	Harbor porpoise	0.5, 1, 2, 4, 8, 16, 32, 63, and 125 kHz	1000 Pa (180 dB)	0.124 s	1452	Kastelein et al. 2015a
Airgun (40-150 in^3)	Bottlenose dolphin (3)	0.25, 0.5, 1, 2, 4, 8, 16, 32, 40, 45, 50, and 64 kHz	31622 Pa (210 dB)	0.3 s	105,407	Finneran et al. 2015

‡ Frequencies in bold indicate those where measurable TTS occurred.

* Ratios in bold text indicate exposure scenarios where measurable TTS occurred.

+ Lucke et al. 2009 did not provide the exact pulse duration in their experiment and only indicated it was less than 0.05 s. NOAA conservatively chose to use 0.05 s for calculating the ratio (i.e., the use of a shorter duration would only result in a higher ratio).

There are limited TTS studies for marine mammals exposed to impulsive sounds, and of those studies only two induced measurable TTS (Finneran et al. 2002; Lucke et al. 2009).

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Nevertheless, these studies help provide insight on ratios where noise-induced hearing loss is possible to occur, with each having a peak pressure to pulse duration ratio of >100,000.

It is important to note that: 1) captive marine mammal TTS studies are completed with animals extremely close to the source (i.e., closer than animals are expected to be to the source in real-world conditions), 2) one of the species where TTS onset occurred is the harbor porpoise (HF cetacean), which is known to have a lower TTS onset acoustic threshold levels (i.e., impulsive and non-impulsive sources) compared to most other cetaceans measured (i.e., MF cetaceans: bottlenose dolphin and beluga), and 3) data provided in Table B3 depict TTS onset (i.e., considered fully recoverable), which is being used to inform where to transition from using impulsive to non-impulsive acoustic threshold levels for PTS onset (i.e., considered non-recoverable; the equivalent ratio expressing PTS onset would have a higher value than the ratio expressing TTS onset). Thus, NOAA has included several conservative factors when considering these data.

1.3 Recommended Transition from Impulsive to Non-Impulsive Acoustic Threshold Levels

Based on previously measured characteristics of impulsive sounds in a variety of environments (Table B2) and using previous marine mammal TTS onset data for impulsive sounds as means of comparison (Table B3), NOAA has determined that a ratio of peak pressure to pulse duration of 5000 is an appropriately precautionary approximation of where most impulsive sound sources begin to transition to having physical characteristics less likely to result in auditory injury. This ratio is considerably lower than any ratio where TTS has been induced in marine mammals from exposure to impulsive sources (i.e., 100,000).

Based on this peak pressure to pulse duration ratio (i.e., 5000), NOAA is recommending 3 km from the source be considered a conservative estimate of transition range for action proponents to consider using non-impulsive to impulsive acoustic thresholds levels. For most sounds, where data are available, a ratio of 5000 typically occurs much closer to the source than our recommended 3 km transition range (i.e., <2 km).

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APPENDIX C: RESEARCH RECOMMENDATIONS FOR IMPROVED ACOUSTIC THRESHOLD LEVELS

In compiling, interpreting, and synthesizing the best available science to produce updated acoustic threshold levels for this Guidance, it is evident that additional data would be useful for future iterations of this document, since many data gaps still exist. The need for identifying and filling critical data gaps was also recommended during the initial peer review and initial public comment period.

Below is a list of research topic recommendations that NOAA believes would help address current data gaps. Some of these areas of recommended research have been previously identified in other publications/reports (e.g., NRC 1994; NRC 2000; Southall et al. 2007; Southall et al. 2009; Hawkins et all 2014; Houser and Moore 2014; Lucke et al. 2014; Popper et al. 2014; Williams et al. 2014). Note: Just because there may not be enough information to allow for quantifiable modifications to acoustic threshold levels associated with many of these recommendations, does not mean these recommendations cannot be incorporated as qualitative considerations within the comprehensive effects analysis.

I. SUMMARY OF RESEARCH RECOMMENDATIONS

1.1 Low-Frequency Cetacean Hearing

As previously stated, direct measurements of LF cetacean hearing are lacking. Therefore, hearing predictions for these species are based on other methods (e.g., anatomical studies, models, vocalizations, taxonomy, and behavioral responses to sound). Thus, additional data[31] collected would be extremely valuable to furthering the understanding of hearing ability within this functional hearing group. For example, data collected on either stranded or animals associated with subsistence hunts would be extremely useful in confirming current predictions of LF cetacean hearing ability and would allow for the development of more accurate auditory weighting functions (e.g., Do species that vocalize at ultra-low frequencies, like blue and fin whales, have dramatically different hearing abilities than other mysticete species?). Until direct measurements can be made, anatomical models will be the primary means of approximating hearing abilities, with validation remaining a critical component of any modeling exercise (e.g., Cranford and Krysl 2014).

1.2 Hearing Diversity Among Species and Auditory Pathways

A better understanding of hearing diversity among species within a functional hearing group is also needed (e.g., Mooney et al. 2014) to comprehend how representative certain species (e.g., bottlenose dolphins, harbor porpoise, harbor seals) are of their functional hearing group as a whole. For example, are there certain species more susceptible to hearing loss

[31] Under appropriate permits or authorizations.

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from sound, or are there additional delineations needed among the current functional hearing groups (e.g., deep diving species, etc.)? This would also help identify if additional functional hearing groups are needed.

Additionally, having a more complete understanding of how sound enters the heads/bodies of marine mammals and its implication on hearing and impacts of noise among various species is another area of importance (e.g., previously undescribed acoustic pathways in odontocetes: Cranford et al. 2008; Cranford et al. 2010; filtering/amplification of transmission pathway: Cranford and Krysl 2012; directional hearing: Renaud and Popper 1975; Au and Moore 1984).

1.3 REPRESENTATIVENESS OF CAPTIVE INDIVIDUALS

Data from Castellote et al. (2014), from free-ranging belugas in Alaska, indicate of the seven healthy individuals tested (3 females/4 males; 1 subadult/6 adults), all had hearing abilities "similar to those of belugas measured in zoological settings." Thus, from this one study, it appears that for baseline hearing measurements, captive individuals may be appropriate surrogates for free-ranging animals. Additionally, Mulsow et al. (2011) measured aerial hearing abilities of seven stranded California sea lions and found a high degree of intersubject variability but that high-frequency hearing limits were consistent with previously tested captive individuals. However, these are currently the only studies of their kind[32], and more research is needed to examine if this trend is applicable to other species

1.3.1 Impacts of Age on Hearing

Hearing loss can result from a variety of factors beyond anthropogenic noise, including ototoxic compounds (chemicals poisonous to auditory structures), disease and infection, and heredity, as well as a natural part of aging (Corso 1959; Kearns 1977; WGSUA 1988; Yost 2007). High-frequency hearing loss, presumably as a normal process of aging that occurs in humans and other terrestrial mammals, has also been demonstrated in captive cetaceans (Ridgway and Carder 1997; Yuen et al. 2005; Finneran et al. 2005b; Houser and Finneran 2006; Finneran et al. 2007b; Schlundt et al. 2011) and in stranded individuals (Mann et al. 2010). Thus, the potential impacts of age on hearing can be a concern when extrapolating from older to younger individuals.

Few studies have examined this phenomenon in marine mammals, particularly in terms of the potential impact of aging on hearing ability and threshold shifts:

- Houser and Finneran (2006) conducted a comprehensive study of the hearing sensitivity of the U.S. Navy bottlenose dolphin population (i.e., tested 42 individuals

[32] NOAA is aware that additional baseline hearing measurements have been recorded for additional free-ranging belugas by Castellote et al. with the analysis still in process. Furthermore, NOAA is aware that audiograms are often obtained during stranding events exists, but these have yet to be published.

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from age four to 47 years; 28 males/14 females). They found that high-frequency hearing loss typically began between the ages of 20 and 30 years. However, the frequencies where this species is most susceptible to noise-induced hearing loss (i.e., 10 to 30 kHz) are the frequencies where the lowest variability exists in mean threshold levels between individuals of different ages.

- Houser et al. (2008) measured hearing abilities of 13 Pacific bottlenose dolphins, ranging in age from 1.5 to 18 years. The author's reported that "Variability in the range of hearing and age-related reductions in hearing sensitivity and range of hearing were consistent with those observed in Atlantic bottlenose dolphins."

- Mulsow et al. (2014) examined aerial hearing thresholds for 16 captive sea lions, from age one to 26 years, and found that only the two 26-year old individuals had hearing classified as "aberrant" compared to other individuals (i.e., high-frequency hearing loss), which were deemed to have similar hearing abilities to previously measured individuals.

- Additionally, for harbor seals, similar exposure levels associated with TTS onset were found in Kastelein et al. 2012a for individuals of four to five years of age compared to that used in Kastak et al. 2005, which was 14 years old and for belugas in Popov et al. 2014 for an individual of 2 years of age compared to those used in Schlundt et al. 2000, which were 20 to 22 years old or 29 to 31 years old.

From these limited data, it appears that age may not be a significant complicating factor, in terms of assessing threshold shifts for animals of different ages. Nevertheless, additional data are needed to confirm if these data are representative for all species.

1.4 ADDITIONAL TTS MEASUREMENTS WITH MORE SPECIES AND/OR INDIVIDUALS

Currently, TTS measurements only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor porpoises, and Yangtze finless porpoise) and three species of pinnipeds (Northern elephant seal, harbor seal, and California sea lion). Additionally, the existing marine mammal TTS measurements are from a limited number of individuals within these species. Having more data from a broader range of species and individuals would be useful to confirm how representative current individuals are of their species and/or entire functional hearing groups. For example, TTS onset threshold levels for harbor porpoise (HF cetacean) is much lower compared to other odontocetes (MF cetaceans), and it would be useful to know if all HF cetaceans share these lower TTS onset threshold levels or if harbor porpoises are the exception.

Sills et al. (2014) recently measured the underwater hearing ability of two captive spotted seals. They found that this species hearing ability is similar to harbor seals, and is lower than other Arctic species tested (i.e., harp and ringed seals). Thus, at least based on data from this one ice seal species, harbor seals may be an appropriate surrogate for ice seal species. As more data become available, this assumption will be re-evaluated.

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Finally, cetaceans are often used as surrogates for pinnipeds when no direct data exist. Having more information on the appropriateness of using cetaceans as surrogates for pinnipeds would be useful (i.e., is there another group more appropriate?).

1.5 Sound Exposure to More Realistic Scenarios

Most marine mammal TTS measurements are for individuals exposed to a limited number of sound sources (i.e., mostly tones and octave-band noise) in laboratory settings. Measurements from exposure to actual sound sources (opposed to tones or octave-band noise) under more realistic exposure conditions (e.g., more realistic exposure durations and/or scenarios) are needed.

Additionally, a better understanding of the effects of multiple sources and multiple activities on threshold shifts, as well of impacts from long-term exposure is needed. Studies on terrestrial mammals indicate that exposure scenarios from complex exposures (i.e., those involving multiple types of sound sources) result in more complicated patterns of noise-induced hearing loss (e.g., Ahroon et al. 1993).

Additionally, Kujawa and Liberman (2009) found that with large, but recoverable thresholds shifts (maximum 40 dB measured by auditory brainstem response (ABR)), sound could cause delayed cochlear nerve degeneration in mice. Furthermore, Lin et al. (2011) reported a similar pattern of neural degeneration in mice after large but recoverable noise-induced threshold shifts (maximum ~50 dB measured by ABR), which suggests a common phenomenon in all mammals. The long-term consequences of this degeneration remain unclear. Another study reported impaired auditory cortex function (i.e., behavioral and neural discrimination of sound in the temporal domain [discriminate between pulse trains of various repetition rates]) after sound exposure was reported in rats that displayed no impairment in hearing (Zhou and Merzenich 2012). Zheng (2012) found reorganization of the neural networks in the primary auditory cortex (i.e., tonotopic map) of adult rats exposed to low-level noise, which suggests an adaptation to living in a noisy environment (e.g., noise exposed rats performed tasks better in noisy environment compared to control rats). Thus, it is recommended that there be additional studies to look at these potential effects in marine mammals (Tougaard et al. 2015).

Furthermore, it is also important to understand how repeated exposures resulting in TTS could potentially lead to PTS (e.g., Kastak et al. 2008; Reichmuth 2009). Nevertheless, noise-induced hearing loss is complex and will continue need to be examined as more data become available.

1.5.1 Protective Mechanisms

Nachtigall and Supin (2013) recently reported that a false killer whale was able to reduce its hearing sensitivity (i.e., conditioned dampening of hearing) when a loud sound was preceded by a warning signal. Nachtigall and Supin (2014) reported a similar finding in a bottlenose

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dolphin, with further study showing that conditioning is associated with the frequency of the warning signal (Nachtigall and Supin 2015). Additionally, Finneran et al. (2015) observed two of the three dolphins displayed "anticipatory" behavior (e.g., head movement) during an exposure sequence to multiple airgun shots. It is unknown if this behavior resulted in some mitigating effects of the exposure.

Thus, marine mammals may have multiple means of reducing or ameliorating the effects noise exposure. However, at this point, directly incorporating them into a comprehensive effects analysis that anticipates the likelihood of exposure ahead of an activity is difficult. More information on these mechanisms, especially associated with real-world exposure scenarios, would be useful.

1.6 IMPACTS OF THRESHOLD SHIFTS ON FITNESS

When considering noise-induced thresholds shifts, it is important to understand that hearing is more than merely the mechanical process of the ear and neural coding of sound (detection). It also involves higher processing and integration with other stimuli (perception) (Yost 2007; Alain and Berstein 2008). Currently, much more is known about the aspects of neural coding of sounds compared to the higher-level processing that occurs on an individual level.

Typically, effects of noise exposure resulting in energetic (Williams et al. 2006; Barber et al. 2010) and fitness consequences (increased mortality or decreased reproductive success) are deemed to have the potential to affect a population/stock (NRC 2005; Southall et al. 2007; SMRU Marine 2014) or as put by Gill et al. 2001 "From a conservation perspective, human disturbance of wildlife is important only if it affects survival or fecundity and hence causes a population to decline." The number of individuals exposed and the location and duration of exposure are important factors, as well. To determine whether a threshold shift will result in a fitness consequence requires one to consider several factors.

First, one has to consider the likelihood an individual would be exposed for long enough duration or to a high enough level to induce a threshold shift (e.g., realistic exposure scenarios). Richardson et al. (1995) hypothesized that "Disturbance effects are likely to cause most marine mammals to avoid any 'zone of discomfort or nonauditory effects' that may exist" and that "The greatest risk of immediate hearing damage might be if a powerful source were turned on suddenly at full power while a mammal was nearby." It is uncertain how frequently individuals in the wild are experiencing situations where TTS and PTS are likely from individual sources (Richardson et al.1995; Erbe and Farmer 2000; Erbe 2002; Holt 2008; Mooney et al. 2009b).

In determining the severity of a threshold shift, it is important to consider the magnitude of the threshold shift, time to recovery (seconds to minutes or hours to days), the frequency range of the exposure, the frequency range of hearing and vocalization for the particular species (i.e., how animal uses sound in the frequency range of anthropogenic noise exposure; e.g., Kastelein et al. 2014b), and their overlap (e.g., spatial, temporal, and spectral).

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Richardson et al. (1995) noted, "To evaluate the importance of this temporary impairment, it would be necessary to consider the ways in which marine mammals use sound, and the consequences if access to this information were impaired." Thus, exposure to an anthropogenic sound source, may affect individuals and species differently (Sutherland 1996).

Finally, different degrees of hearing loss exist: ranging from slight/mild to moderate and from severe to profound (Clark 1981), with profound loss being synonymous with deafness (CDC 2004; WHO 2006). For hearing loss in humans, Miller (1974) summarized "any injury to the ear or any change in hearing threshold level that places it outside the normal range constitutes a hearing impairment. Whether a particular impairment constitutes a hearing handicap or a hearing disability can only be judged in relation to an individual's life pattern or occupation." This statement can translate to considering effects of hearing loss in marine mammals, as well (i.e., replacing "occupation" for "fitness").

Simply because a hearing impairment may be possible does not necessarily mean an individual will experience a disability in terms of overall fitness consequence. However, there needs to be a better understanding of the impacts of repeated exposures. As Kight and Swaddle (2011) indicate "Perhaps the most important unanswered question in anthropogenic noise research – and in anthropogenic disturbance research, in general – is how repeated exposure over a lifetime cumulatively impacts an individual, both over the short- (e.g. condition, survival) and long- (e.g., reproductive success) term." Thus, more research is needed to understand the true consequences of noise-induced threshold shifts (acute and chronic) to overall fitness.

1.7 Behavior of Marine Mammals Under Exposure Conditions with the Potential to Cause Hearing Impacts

Although assessing the behavioral response of marine mammals to sound is outside the scope of this document, understanding behavioral responses of marine mammals to sound, especially in terms of exposure conditions having the potential to cause noise-induced hearing loss is critical to be able to predict exposure better. Understanding behavioral responses of marine mammals to anthropogenic sound exposure presents a set of unique challenges, which arise from the inherent complexity of behavioral responses. Responses can depend on numerous factors, including intrinsic, natural extrinsic (e.g., ice cover, prey distribution), or anthropogenic , as well as the interplay among factors (Archer et al. 2010). Behavioral reactions can vary not only among individuals but also within an individual, depending on previous experience with a sound source, hearing sensitivity, sex, age, reproductive status, geographic location, season, health, social behavior, or context.

Severity of responses can also vary depending on characteristics associated with the sound source (e.g., whether it is moving or stationary, number of sound sources) or the potential of source and individuals co-occurring temporally and spatially (e.g., persistence or recurrence of the sound in specific areas; how close to shore, region where animals may be unable to avoid exposure, propagation characteristics that are either enhancing or reducing exposure)

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(Richardson et al. 1995; NRC 2003; Wartzok et al. 2004; NRC 2005; Southall et al. 2007; Bejder et al. 2009).

Furthermore, not all species or individuals react identically to anthropogenic sound exposure. There may be certain species-specific behaviors (e.g., fight or flight responses, particularly sensitive species) that make a species or individuals of that species more likely to react to anthropogenic sound. Having this information would be useful in improving recommended baseline accumulations periods and understanding situations where individuals are more likely to be exposed to noise over longer durations and are more at risk for noise-induced losses in hearing, either temporary or permanent.

1.8 Characteristics of Sound Associated with Injury and Impacts of Propagation

It is known as sound propagates through the environment various physical characteristics change (e.g., frequency content with lower frequencies typically propagating further than higher frequencies; pulse length due to reverberation or multipath propagation in shallow and deep water). Having a better understanding of the characteristics of a sound that makes it injurious (e.g., peak pressure amplitude, rise time, pulse duration, etc.; Henderson and Hamernik 1986; NIOSH 1998) and how those characteristics change under various propagation conditions would be extremely helpful in the application of appropriate thresholds and be useful in supporting or further revising NOAA's methodology for transitioning from the use of impulsive to non-impulsive thresholds at 3 km from the source.

1.9 Threshold Shift Growth Rates and Recovery

Threshold shift growth rate data for marine mammals is limited and has been found to be higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran and Schlundt 2013). Understanding how these trends vary with exposure to more complex sound sources (e.g., broadband impulsive sources) and among various species would be valuable.

Understanding recovery after sound exposure is also an important consideration. Currently, there is a lack of recovery data for marine mammals, especially for exposure to durations and levels expected under real-world scenarios. Thus, additional marine mammal noise-induced recovery data would be useful. A better understanding of likely exposure scenarios, including the potential for recovery could also improve recommended baseline accumulation periods (e.g., time constant associated with leaky integrator model).

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1.10 METRICS AND TERMINOLOGY

Sound can be described using a variety of metrics, with some being more appropriate sound types or effects compared with others (e.g., Coles et al. 1968; Hamernik et al. 2003; Madsen 2005; Davis et al. 2009; Zhu et al. 2009). A better understanding of the most appropriate metrics for establishing acoustic threshold levels and predicting impacts to hearing would be useful in confirming the value of providing dual metric thresholds using the peak pressure and cumulative sound exposure level metrics. As science advances, additional or more appropriate metrics may be identified and further incorporated by NOAA. However, caution is recommended when comparing sound descriptions in different metrics (i.e., they are not directly comparable). Additionally, the practicality of measuring and applying metrics is another important consideration.

Furthermore, current auditory threshold levels are based on the EEH, which known to be inaccurate in some situations. Recently, Popov et al. 2014 suggested that SPL multiplied by log duration better described their data than the EEH. Thus, better means of describing the interaction between SPL and duration of exposure would be valuable.

Finally, in trying to define metrics and certain terms (e.g., impulsive and non-impulsive, functional hearing) within the context of the Guidance, NOAA often found difficulties due to lack of universally accepted standards and common terminology. Thus, NOAA encourages the further development of these.

1.11 EFFECTIVE QUIET

"Effective quiet" is defined as the maximum sound pressure level that will fail to produce any significant threshold shift in hearing despite duration of exposure and amount of accumulation (Ward et al. 1976; Ward 1991). Effective quiet can essentially be thought of as a "safe exposure level" (i.e., risks for threshold shifts are extremely low or nonexistent) in terms of hearing loss[33] (Mills 1982; NRC 1993) and is frequency dependent (Ward et al. 1976; Mills 1982). Effective quiet is an important consideration for the onset TTS and PTS acoustic threshold levels expressed by the SEL_{cum} metric because if not taken into consideration unrealistically low levels of exposure with long enough exposure durations could accumulate to SEL_{cum} exceeding current acoustic threshold levels, when the likelihood of threshold shift is extremely low (e.g., humans exposed to continuous levels of normal speech levels throughout the day are not typically subjected to TTS from this type of exposure).

Currently, defining effective quiet for marine mammals is not possible due to lack of data. However, a recent study by Popov et al. 2014 for belugas exposed to half-octave noise centered at 22.5 kHz indicates that effective quiet for this exposure scenario and species

[33] Note: "Effective quiet" only applies to hearing loss and not to behavioral response (i.e., levels below "effective quiet" could result in behavioral responses). It also is separate consideration from defining "quiet" areas (NMFS 2009).

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might be around 154 dB. As more data become available, they would be useful in contributing to the better understanding of appropriate accumulations periods for the SEL_{cum} metric and noise-induced hearing loss.

1.12 TRANSLATING BIOLOGICAL COMPLEXITY INTO PRACTICAL APPLICATION

Although, not a specific research recommendation, the consideration of practical application of science is important. As more is learned about the effects of sound on marine mammals, the more complex future acoustic thresholds levels are likely to become. For example, before this Guidance, NOAA primarily relied on two generic thresholds for assessing auditory impacts, with one for cetaceans (180 dB_{rms}) and one for pinnipeds (190 dB_{rms}). In this document, these two simple thresholds have now been replaced by ten thresholds in dual metrics for PTS, including the addition of auditory weighting functions. Although, these updated acoustic threshold levels better represent the current state of knowledge, they have created additional challenges for implementation. Practical application always needs to be weighed against making acoustic thresholds overly complicated (cost vs. benefit considerations). The creation of tools to help ensure complex thresholds are applied correctly by action proponents, as well as managers, is definitely needed.

Additionally, there is always a need for basic, practical acoustic training opportunities for action proponents and managers (most acoustic classes available are for students and not necessarily those who deal with acoustics in a more applied way).

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APPENDIX D: PEER REVIEW PROCESS AND PUBLIC COMMENT PERIOD

I. PEER REVIEW PROCESS

The President's Office Management and Budget (OMB 2005) states "Peer review is one of the important procedures used to ensure that the quality of published information meets the standards of the scientific and technical community. It is a form of deliberation involving an exchange of judgments about the appropriateness of methods and the strength of the author's inferences. Peer review involves the review of a draft product for quality by specialists in the field who were not involved in producing the draft."

The peer review of this document was conducted in accordance with NOAA's Information Quality Guidelines[34] (IQG), which were designed for "ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency" (with each of these terms defined within the IQG). Furthermore, the IQG stipulate that "To the degree that the agency action is based on science, NOAA will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods." Under the IQG and in consistent with OMB's Final Information Quality Bulletin for Peer Review (OMB Peer Review Bulletin (OMB 2005), the Guidance was considered a Highly Influential Scientific Assessments (HISA)[35], and peer review was required before it could be disseminated by the Federal Government. OMB (2005) notes "Peer review should not be confused with public comment and other stakeholder processes. The selection of participants in a peer review is based on expertise, with due consideration of independence and conflict of interest."

The peer review of the Guidance consisted of three independent reviews covering various aspects of the Guidance: 1) There was an initial peer review of the entire draft Guidance in 2013, 2) a second peer review in March/April 2015 that focused on newly available science from the U.S. Navy (See Appendix A), and 3) finally a third peer review in April 2015 in response to public comments received during the initial public comment period, which focused on a particular technical section relating to the Guidance's proposed application of impulsive and non-impulsive PTS acoustic threshold levels based on physical characteristics at the source and how those characteristics change with range (See Section 2.3.1 of main document and Appendix B). Upon completion of the three peer reviews, NOAA was required to post and respond to all peer reviewer comments received via three separate Peer Review Reports.

[34] http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html

[35] "its dissemination could have a potential impact of more than $500 million in any one year on either the public or private sector; or that the dissemination is novel, controversial, or precedent-setting; or that it has significant interagency interest" (OMB 2005).

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1.1 INITIAL PEER REVIEW

For the initial peer review of this document (July to September 2013), potential qualified peer reviewers were nominated by a steering committee put together by the Marine Mammal Commission (MMC). The steering committee consisted of MMC Commissioners and members of the Committee of Scientific Advisors (Dr. Daryl Boness, Dr. Douglas Wartzok, and Dr. Sue Moore).

Nominated peer reviewers were those with expertise marine mammalogy, acoustics/bioacoustics, and/or acoustics in the marine environment. Of the ten nominated reviewers, four were selected as peer reviewers to complete an individual review of the document based on area of expertise[36] and availability (Table D1). The focus of the peer review was on the scientific and technical studies that have been applied and the manner that they have been applied in this document.

Table D1: Initial peer review panel.

Name	Affiliation
Dr. Paul Nachtigall	University of Hawaii
Dr. Doug Nowacek	Duke University
Dr. Klaus Lucke*	Wageningen University and Research (The Netherlands)
Dr. Aaron Thode	Scripps Institution of Oceanography
* Present affiliation: Curtin University (Australia)	

Peer reviewers' comments and NOAA's responses to the comments, from this initial peer review, can be found at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

1.2 SECOND PEER REVIEW

For their Phase 3 Acoustic Effects Analysis, the U.S. Navy provided NMFS with a technical report describing their proposed methodology for updating auditory weighting functions and subsequent numeric thresholds for predicting auditory effects (TTS/PTS thresholds) on marine animals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns utilized during Navy training and testing activities.

Upon evaluation, NOAA preliminarily determined that the Navy's proposed methodology reflected the best available science and decided to incorporate it into the Guidance. Before doing so, we commissioned an independent peer review of the Navy's technical paper (i.e.

[36] Reviewer credentials are posted at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

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second peer review). Note: Reviewers were not asked to review the entire Guidance document.

For the second peer review (March to April 2015), NOAA again requested the assistance of the MMC to nominate peer reviewers. As with the initial peer review, potential qualified peer reviewers were nominated by a steering committee put together by the MMC, which consisted of MMC Commissioners and members of the Committee of Scientific Advisors (Dr. Daryl Boness, Dr. Douglas Wartzok, and Dr. Sue Moore).

Nominated peer reviewers were those with expertise[37] specifically in marine mammal hearing (i.e., behavior and/or AEP) and/or noise-induced hearing loss. Of the twelve nominated reviewers, four were selected as peer reviewers to complete an individual review of the Navy's technical document based on area of expertise and availability (Table D2).

Table D2: Second peer review panel.

Name	Affiliation
Dr. Whitlow Au	University of Hawaii
Dr. Colleen Le Prell	University of Florida
Dr. Klaus Lucke	Curtin University (Australia)
Dr. Jack Terhune	University of New Brunswick (Canada)

Peer reviewers' comments and NOAA's responses to the comments, from the second peer review, can be found at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

1.3 THIRD PEER REVIEW

During the Guidance's initial public comment period, NOAA received numerous comments relating to how the Guidance classifies acoustic sources based on characteristics at the source (i.e., non-impulsive vs. impulsive). Many expressed concern that as sound propagates through the environment and eventually reaches a receiver (i.e., marine mammal) that physical characteristics of the sound may change and that NOAA's categorization may not be fully reflective of real-world scenarios. Thus, NOAA re-evaluated its methodology for categorizing sound sources to reflect these concerns. Thus, a third peer review focused on particular technical section relating to the Guidance's proposed application of impulsive and non-impulsive PTS acoustic threshold levels based on physical characteristics at the source and how those characteristics change with range. Note: Reviewers were not asked to review the entire Guidance document.

[37] Reviewer credentials are posted at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

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Since the focus of the third peer review was focused on the physical changes a sound experiences as it propagates through the environment, the Acoustical Society of America's Underwater Technical Council was asked to nominate peer reviewers with expertise in underwater sound propagation and physical characteristics of impulsive sources, especially high explosives, seismic airguns, and/or impact pile drivers. Of the six nominated reviewers, two were selected as peer reviewers to complete an individual review of the technical section based on area of expertise[38] and availability (Table D3).

Additionally, NOAA wanted peer reviewers with expertise in marine and terrestrial mammal noise-induced hearing loss to review this technical section and ensure the proposed methodology was ground-truthed in current biological knowledge. Thus, NOAA re-evaluated peer reviewer nominees previously made by the MMC and selected two reviewers based on area of expertise[60] and availability (Table D3).

Table D3: Third peer review panel.

Name	Affiliation
Dr. Robert Burkard	University at Buffalo
Dr. Peter Dahl*	University of Washington
Dr. Colleen Reichmuth+	University of California Santa Cruz
Dr. Kevin Williams*	University of Washington

* Peer reviewers with expertise in underwater acoustic propagation

\+ Dr. Reichmuth was an alternate on the MMC original peer reviewer nomination list

Peer reviewers' comments and NOAA's responses to the comments, from the third peer review, can be found at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

1.4 Conflict of Interest Disclosure

Each peer reviewer (i.e., initial, second, and third peer review) completed a conflict of interest disclosure form. It is essential that peer reviewers of NOAA influential scientific information or highly influential scientific assessments not be compromised by any significant conflict of interest. For this purpose, the term "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it (1) could significantly impair the individual's objectivity or (2) could create an unfair competitive advantage for any person or organization. No individual can be appointed to review information subject to the OMB Peer Review Bulletin if the individual has a conflict of interest that is relevant to the functions to be performed.

[38] Reviewer credentials are posted at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

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The following website contains updated information on the peer review process including: the charge to peer reviewers, peer reviewers' names, peer reviewers' individual reports, and NOAA's response to peer reviewer reports: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

II. PUBLIC COMMENT PERIODS

In addition to the peer review process, NOAA recognizes the importance of feedback from action proponents/stakeholders and among other members of the public. The focus of the public comment process was on both the technical aspects of the document, as well as the implementation of the science in NOAA's policy decisions under the various applicable statutes. Public comment periods were held after the peer reviews to ensure the public received the most scientifically strong product to provide comments.

2.1 INITIAL PUBLIC COMMENT PERIOD

A public meeting/webinar was held to inform interested parties and solicit comments on the first publicly available version of the Draft NOAA Guidance. The meeting/webinar was held on January 14, 2014, in the NOAA Science Center in Silver Spring, Maryland. The presentation and transcript from this meeting is available electronically (http://www.nmfs.noaa.gov/pr/acoustics/publicmeeting_transcript.pdf).

This public comment period was advertised via the Federal Register and originally lasted 30 day and opened on December 27, 2013 (NMFS 2013). During this 30-day period, multiple groups requested that the public comment period be extended beyond 30 days. Thus, the public comment period was extended an additional 45 days and closed on March 13, 2014 (NMFS 2014).

2.1.1 Summary of Public Comments Received

A total of 129[39] comments were received from individuals, groups, organizations, and affiliations. Twenty-eight of these were in the form of a letter, spreadsheet, or individual comment submitted by representatives of a group/organization/affiliation (some submitted on behalf of an organization and/or as an individual). Those commenting included: 11 members of Congress; 8 state/federal/international government agencies; 2 Alaskan native groups; 7 industry groups; 5 individual subject matter experts; 1 scientific professional organization; 12 non-governmental organizations; 1 consulting firm; and a regulatory watchdog group. Each provided substantive comments addressing technical aspects and/or

[39] Of this number, one comment was directed to the Federal Communications Commission (i.e., not meant for the Guidance) and one commenter submitted their comments twice. In addition, one comment was not included in this total, nor posted because it contained threatening language.

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issues relating to the implementation of updated threshold levels, which were addressed in the Final Guidance[40].

Of those not mentioned above, an additional 101 comments were submitted in the form of a letter or individual comment. Twelve of these comments specifically requested an extension of the original 30-day public comment period (a 45-day extension to original public comment period was granted). The remaining 89 comments were not directly applicable to the Guidance (e.g., general concern over impacts of noise on marine mammals from various industry or military activities) and were not further addressed. Specific comments can be viewed on Regulations.gov: http://www.regulations.gov/#!docketDetail;D=NOAA-NMFS-2013-0177.

PLACEHOLDER: NOAA responses to the initial public comment **will be** published in the Federal Register located on the following web site when the Guidance is finalized: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

2.2 SECOND PUBLIC COMMENT PERIOD

Because of the significant changes made to the Draft Guidance from the two additional peer reviews, NOAA proposed a second 45-day public comment, which occurred in the summer of 2015. This public comment period was advertised via the Federal Register and opened on July **31**, 2015 (**PLACEHOLDER for** Federal Register Notice: NMFS 2015).

2.2.1 Summary of Public Comments Received

PLACEHOLDER: Summary will be provided after close of second public comment period.

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[40] With the updates made to the Guidance during the second and third peer review, some of the comments made during the initial public comment period were no longer relevant and as such were not addressed.

APPENDIX E: OPTIONAL ALTERNATIVE METHODOLOGY

I. INTRODUCTION

This Appendix is provided to assist action proponents in the application of the updated acoustic thresholds levels presented in this Guidance. Since the adoption of NOAA's original thresholds for assessing auditory impacts, the understanding of the effects of noise on marine mammal hearing has greatly advanced (e.g., Southall et al. 2007; Finneran 2015) making it necessary to re-examine the current state of science and our acoustic threshold levels. However, NOAA recognizes in updating our acoustic threshold levels to reflect the best available science, they have become more complex.

This Appendix provides a set of tools, examples, and alternative threshold levels to allow action proponents with different levels of exposure modeling capabilities to be able to accurately apply NOAA's updated acoustic threshold levels for the onset of temporary threshold shifts (TTS) and permanent threshold shifts (PTS) for all sound sources.

Action proponents are not obligated to use this Appendix and are encouraged to perform more sophisticated modeling or consider additional action- or location-specific factors, if able.

II. ALTERNATIVE ACOUSTIC THRESHOLD LEVELS

Numerical criteria presented in the Guidance consist of both an acoustic threshold level and auditory weighting function associated with the cumulative sound exposure level (SEL_{cum}) metric. NOAA recognizes that the implementation of marine mammal weighting functions represents a new factor for consideration, which may extend beyond the capabilities of some action proponents. Thus, NOAA has developed alternative acoustic threshold levels for those who cannot fully apply auditory weighting functions associated with the SEL_{cum} metric (Table E1).

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Table E1: Alternative PTS and TTS onset dual acoustic threshold levels*. NB stands for narrowband.

	PTS Onset (Received Level)		TTS Onset (Received Level)	
Hearing Group	**Impulsive**	**Non-Impulsive**	**Impulsive**	**Non-Impulsive**
Low-Frequency (LF) Cetaceans	**Source: All** 230 dB_{peak} **&** 192 dB SEL_{cum}	**Source: All** 230 dB_{peak} **&** 207 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 177 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 187 dB SEL_{cum}
Mid-Frequency (MF) Cetaceans	**Source: All** 230 dB_{peak} **&** 200 dB SEL_{cum}	**Source: NB ≥3 kHz** 230 dB_{peak} **&** 199 dB SEL_{cum} **Source: All others** 230 dB_{peak} **&** 212 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 185 dB SEL_{cum}	**Source: : NB ≥3 kHz** 224 dB_{peak} **&** 179 dB SEL_{cum} **Source: All others** 224 dB_{peak} **&** 192 dB SEL_{cum}
High-Frequency (HF) Cetaceans	**Source: All** 202 dB_{peak} **&** 177 dB SEL_{cum}	**Source: NB ≥ 3 kHz** 202 dB_{peak} **&** 171 dB SEL_{cum} **Source: All others** 202 dB_{peak} **&** 194 dB SEL_{cum}	**Source: All** 196 dB_{peak} **&** 162 dB SEL_{cum}	**Source: NB ≥ 3 kHz** 196 dB_{peak} **&** 151 dB SEL_{cum} **Source: All others** 196 dB_{peak} **&** 174 dB SEL_{cum}
Phocid Pinnipeds (Underwater)	**Source: All** 230 dB_{peak} **&** 186 dB SEL_{cum}	**Source: All** 230 dB_{peak} **&** 201 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 171 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 181 dB SEL_{cum}
Otariid Pinnipeds (Underwater)	**Source: All** 230 dB_{peak} **&** 203 dB SEL_{cum}	**Source: All** 230 dB_{peak} **&** 218 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 188 dB SEL_{cum}	**Source: All** 224 dB_{peak} **&** 198 dB SEL_{cum}

* Dual acoustic threshold levels: Use whichever [dB_{peak} or dB SEL_{cum}] exceeded first. These alternative acoustic threshold levels are based on whether the sound pressure levels from the source are predominantly within the most susceptible hearing range of the auditory weighting function for a functional hearing group.

Note: In this Table, dB_{peak}, is equivalent to the ANSI abbreviation of L_{pk} and SEL_{cum} is equivalent to the ANSI abbreviation of L_E (ANSI 2013).

Action proponents are encouraged to incorporate complex factors, such full auditory weighting functions, into their exposure models. However, NOAA recognizes this may not be possible for all action proponents or for all activities and has created alternative threshold levels.

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Alternative acoustic thresholds levels are weighted but consider marine mammal auditory weighting functions in broad steps. The use of these alternative acoustic threshold levels typically results in a higher number of predicted exposures compared to those action proponents that can fully apply weighting functions.

Note: Action proponents should confirm that sources adhere manufacturer specifications and that they only produce sound within the specified frequency (i.e., sometimes sources are capable of producing sounds outside their specified bands; Deng et al. 2014; Hastie et al. 2014). If it is unclear whether a source is narrowband or not, please consult with NOAA.

2.1 Derivation of Alternative Acoustic Threshold Levels

When dividing marine mammal auditory weighting functions in broader steps to produce alternative threshold levels, several factors were taken into consideration. Specifically, NOAA considered the most susceptible hearing range associated with a functional hearing group, as well as the frequency ranges of sound sources typically evaluated in NOAA analyses. Based on these criteria, NOAA decided to divide the auditory weighting function for MF and HF cetaceans into two broad steps:

1) Sound within the most susceptible hearing range of the functional hearing group (i.e., enhanced hearing sensitivity and susceptibility to noise-induced hearing loss)

2) Sound predominantly outside the susceptible frequency range of the functional hearing group

For the MF and HF cetaceans, the demarcation between these two broad steps was set at 3 kHz (Figure E1). The alternative acoustic threshold levels are based on an assumption that the most common impulsive sources (i.e., airguns, impact pile drivers) and broadband, non-impulsive sounds produce the majority[41] of their sound pressure level at lower frequencies (i.e., below 3 kHz; e.g., seismic: Greene and Richardson 1988; Breitzke et al. 2008; pile driving: Blackwell et al. 2004a; Blackwell 2005; Bailey et al. 2010; Caltrans 2012; drilling: Greene 1987; Blackwell et al. 2004b), which is outside the most susceptible hearing range of MF and HF cetaceans. If there is an impulsive or a non-impulsive, broadband source with the majority of its sound pressure level above 3 kHz, then the alternative acoustic threshold levels be modified by NOAA (case-by-case basis).

Note: Acoustic threshold levels, associated with sound sources with the majority of their sound energy below 3 kHz, are adjusted only by the weighting function amplitude at 3 kHz (i.e., if an action proponent was able to fully apply the MF and HF auditory weighting functions, there we would be an even larger adjustment a frequencies below 3 kHz, which

[41] NOAA acknowledges there may be certain circumstances where sources, like seismic airguns, are capable at producing sound at higher frequencies (i.e., above 3 kHz; e.g., Goold and Fish 1998). In those situations, further evaluation may be needed to decide whether these sources produce enough higher-frequency energy for there to be enhanced susceptibility for noise-induced hearing loss in these functional hearing groups.

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would result in a lower number of predicted exposures). Additionally, NOAA acknowledges that HF cetaceans have lower PTS and TTS onset acoustic threshold levels compared to other cetaceans. By using a 3 kHz demarcation between the two broad steps of the weighting function, a broader range of frequencies (i.e., above 3 kHz) are considered to be within the most susceptible hearing range for this functional hearing group compared to MF cetaceans (i.e., if the same amplitude of -13 dB was used for HF cetaceans, as it is for MF cetaceans, then this would occur at ~ 6.5 kHz, instead of the 3 kHz as suggested in this document).

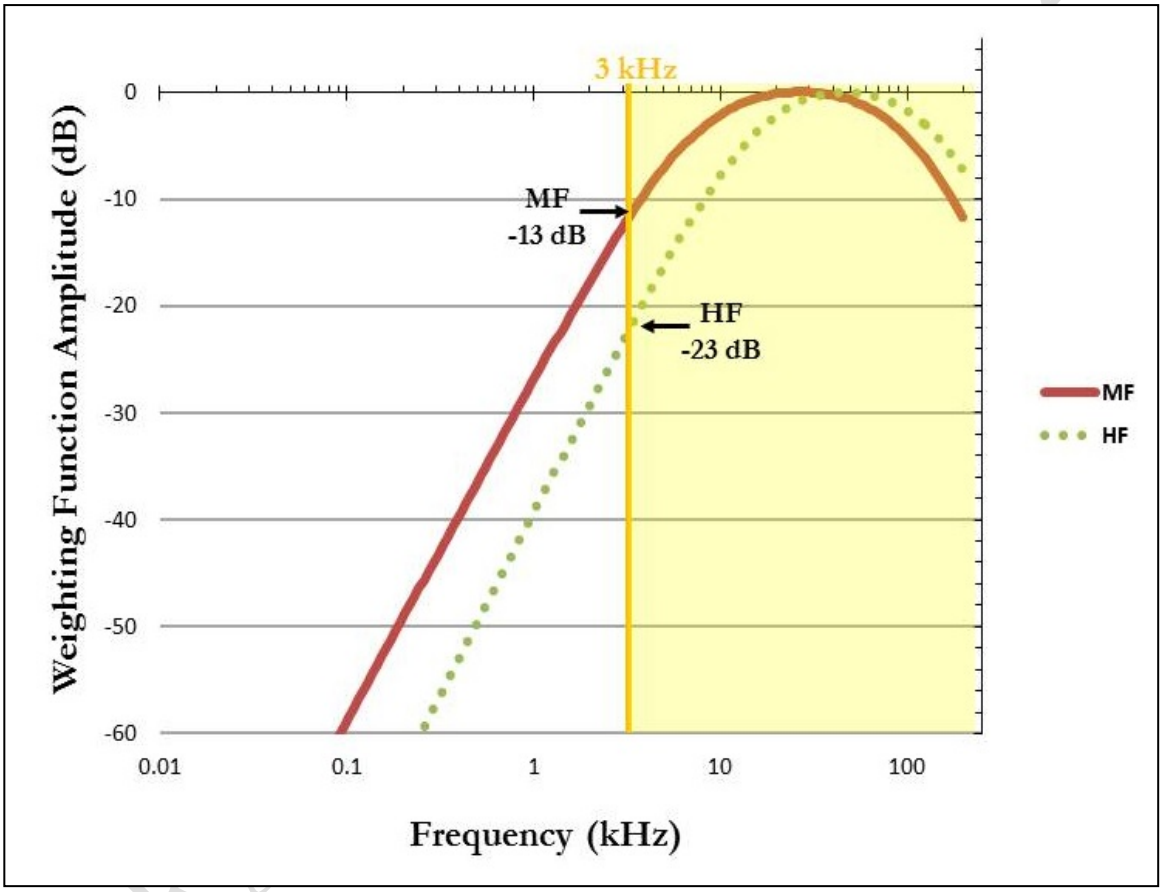


Figure E1: Most susceptible frequency range for mid- (MF), and high-frequency (HF) cetaceans illustrated by the transparent yellow box above 3 kHz. The weighting function amplitude is -13 dB for MF cetaceans and -23 dB for HF cetaceans at 3 kHz.

For the other functional hearing groups (i.e., phocid and otariid pinnipeds and LF cetaceans), NOAA determined that the majority of sound sources had energy within some band of these group's most susceptible frequency range. Thus, dividing the auditory weighting functions into two broad steps for these other functional hearing groups was deemed unnecessary (i.e., the majority of sound sources, unless near the edge of the groups

functional hearing range, would never fall outside the group's most susceptible frequency range).

2.2 EXAMPLE APPLICATIONS OF ALTERNATIVE ACOUSTIC THRESHOLD LEVELS

Below are example scenarios to illustrate how alternative acoustic threshold levels could be applied.

2.2.1 Broadband Low-Frequency Non-Impulsive Source (e.g., drilling, vibratory pile driving)

In this example, a broadband source contains frequencies primarily below 3 kHz (e.g., drilling and vibratory pile driving), which is outside the most susceptible frequency range for MF and HF cetaceans. Thus, the potential for noise-induced hearing loss is deemed lower for these functional hearing groups, and a 23 dB higher[42] SEL_{cum} PTS onset acoustic threshold level is applied for HF cetaceans (i.e., 194 dB SEL_{cum} opposed to 171 dB SEL_{cum}) and a 13 dB higher SEL_{cum} PTS onset acoustic threshold level is applied for MF cetaceans (i.e., 212 dB SEL_{cum} opposed to 199 dB SEL_{cum}).

For pinnipeds (phocids and otariids) and LF cetaceans, these sources are within the functional hearing groups' most susceptible frequency ranges. Thus, the alternative thresholds match those presented in the Guidance (i.e., no alternative threshold levels are provided).

2.2.2 Narrowband Non-Impulsive Source Above 35 kHz (e.g., sonar)

In this example, narrowband sonar contains frequencies above 30 kHz. This source is within the most susceptible frequency range for MF and HF cetaceans. Thus, the alternative thresholds match those presented in the Guidance (i.e., no adjustment is made).

Furthermore, no adjustments would be made for phocid or otariid pinnipeds, since this source is still considered within these functional hearing groups' most sensitive range (based on the criteria of this Appendix). Note: This specific source is outside the functional hearing range for LF cetaceans and does not need to be considered by the action proponent.

2.2.3 Broadband Impulsive Source (e.g., impact pile driving, seismic airgun)

In this example, a broadband source contains frequencies primarily below 3 kHz (e.g., drilling and vibratory pile driving), which is outside the most susceptible frequency range for

[42] Higher compared to the acoustic threshold levels presented in the Guidance. Adjustments (dB) are based on results from Equation 1 in in main document.

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MF and HF cetaceans. Thus, the potential for noise-induced hearing loss is deemed lower for these functional hearing groups, and a 23 dB higher SEL_{cum} PTS onset acoustic threshold level is applied for HF cetaceans and a 13 dB higher SEL_{cum} PTS onset acoustic threshold level is applied for MF cetaceans.

Since the majority of known sources contain frequencies primarily below 3 kHz, only one alternative threshold is provided for MF and HF cetaceans (opposed to two for these functional hearing groups and non-impulsive sounds). Again, if an impulsive or a non-impulsive is broadband and the majority of its sound pressure level above 3 kHz, then the alternative acoustic threshold levels would be modified by NOAA (case-by-case basis).

III. MODELING CUMULATIVE SOUND EXPOSURE LEVELS

To apply the PTS onset auditory threshold levels expressed as the cumulative sound exposure level metric (SEL_{cum}), accumulation time must be specified. Generally, it is predicted that most receivers will minimize their time in closest ranges to a sound source/activity and that exposures at the closest point of approach that are the primary exposures contributing to a receivers accumulated level (Gedamke et al. 2011). Additionally, several important factors determine the likelihood and duration of time a receiver is expected to be in close proximity to a sound source (i.e., overlap in space and time between the source and receiver). For example, accumulation time for fast moving (relative to the receiver), mobile source, is driven primarily by the characteristics of source (i.e., speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and whether transient or resident to the area where the activity is occurring). For all sources, NOAA recommends a baseline accumulation period of 24-h, but acknowledges that there may be specific exposure situations where this accumulation period requires adjustment by action proponent (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations).

Previous NOAA acoustic threshold levels proposed only accounted for proximity of the sound source to the receiver, but acoustic threshold levels in the Guidance (i.e., expressed as SEL_{cum}) now take into account the duration of exposure. NOAA recognizes that accounting for duration of exposure, although supported by the best available science, adds a new factor, as far as application of this metric to real-world activities and that all action proponents may not have the ability to easily incorporate this additional component. NOAA does not provide specifications necessary to perform exposure modeling and relies on the action proponent to determine the model that best represents their activity.

3.1 MORE SOPHISTICATED MODELS

Because of the time component associated with the SEL_{cum} metric, the use of different types of models to predict sound exposure may necessitate different approaches in evaluating likely effects in the context of the PTS onset acoustic threshold levels. All marine mammals

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and some sources move in space and time, however, not all models are able to simulate relative source and receiver movement. Additionally, some models are able to predict the received level of sound at each modeled animal (often called animats) and accumulate sound at these receivers while incorporating the changing model environment.

More sophisticated models may allow for the inclusion of added details to achieve more realistic results based on the accumulation of sound (e.g. information on residence time of individuals, swim speeds for transient species, or specific times when activity temporarily ceases). Alternatively, there may be case-specific circumstances where the accumulation time should be modified to account for situations where animals are expected to be in closer proximity to the source over a significantly longer amount of time, based on activity, site, and species-specific information (e.g., where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and a long-duration activity with a large sound source, or a continuous stationery activity nearby a pinniped pupping beach).

3.2 LESS SOPHISTICATED MODELS

For action proponents unable to incorporate animal and/or source movement, it may not be realistic to assume that animals will remain at a constant distance from the source accumulating acoustic energy for 24 hours. Thus, alternative methods are needed, which can provide a distance from the source where exposure exceeding a threshold is expected to occur ("SEL_{cum} threshold distance") and can be used in the same manner as distance has been used to calculate exposures above previous NOAA thresholds. NOAA proposes two optional alternative methods: one for mobile sources and one for stationary sources.

3.2.1 Mobile Sources: Safe Distance[43]

Cumulative sound exposure can be computed using a simple equation, assuming a constant received sound pressure level (SPL) that does not change over space and time[44] (Equation E1.; e.g., Urick 1983; ANSI 1986; Madsen 2005):

$$SEL_{cum} = SPL\ (dB) + 10 \log_{10} (\text{duration of exposure, expressed in seconds})$$

Equation E1

[43] The safe distance methodology presented in this Appendix underwent peer review via the publication process (Sivle et al. 2014) but did not undergo a separate peer review. It is an optional tool for the application of the acoustic thresholds presented in the Guidance.

[44] Equation 1 assumes a constant source-receiver separation distance.

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However, if one assumes a stationary receiver and a source moving at a constant speed in a constant direction, then exposure changes over space and time (i.e., greatest rate of accumulation of exposure at closest point of approach).

An alternative approach for modeling moving sources is the concept of a "safe distance," which is defined by Sivle et al. (2014) as "the distance from the source beyond which a threshold for that metric (SPL_0 or SEL_0) is not exceeded." The concept of safe distance allows one to determine at what distance from a source a receiver would have to remain in order not to exceed a predetermined exposure threshold (i.e., E_0 which equals PTS onset threshold level in this Guidance). This concept is further illustrated in Figure E2.

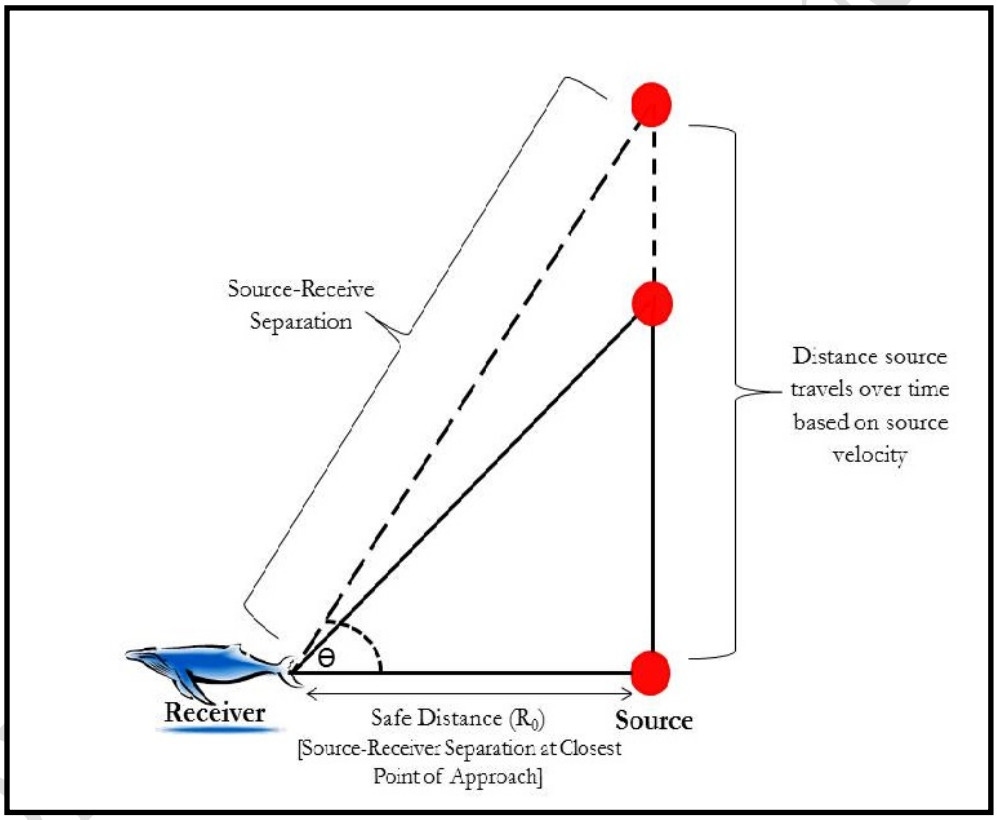


Figure E2: Illustration of concept of safe distance, with each red dot representing the source traveling over time. As the source travels further from the receiver, the source-receiver separation increases (i.e., hypotenuse gets longer).

The "safe distance" (R_0) accounts for several factors, including source level, interpulse interval or duty cycle, and velocity of the source and is independent of exposure duration (Equations 2Ea,b).

Once the safe distance has been determined, it represents the exposure isopleth calculated using NOAA's previous acoustic threshold levels. Thus, area calculations and exposure calculations would be performed in the same manner[45] action proponents have previously used (e.g., determine area covered over a 24-h period multiplied by the density of a marine mammal species).

Safe distance is calculated via the following equation[46]:

a

$$R_0 = \frac{\pi}{E_0 v} SD$$

OR **Equations 2Ea,b**

For impulsive sources, SD is replaced with S_E/τ:

b

$$R_0 = \frac{\pi}{E_0 v} \frac{S_E}{\tau}$$

where:

S = source factor ($10^{(SL/(10\ dB))}$)
D =duty cycle (pulse length/interpulse interval)
v= velocity (meter/second)
E_0 =exposure threshold ($10^{(PTS\ acoustic\ threshold\ level/10\ dB)}$)
S_E = energy source factor ($10^{(SL_E/(10\ dB))}$)
τ = repetition time (second)

The safe distance approach considers four factors:

1. Source level (direct relationship: as source level increases, so does the safe distance).
2. Duty cycle or repetition time (direct relationship: as duty cycle increases, so does the safe distance).
3. Source velocity (inverse relationship: as source velocity decreases, the safe distance increases or vice versa).

[45] Note: "Take" calculations are typically based on speed expressed in kilometers per hour, duration of an exposure expressed in hours (i.e., 24 hours), safe distances expressed in kilometers, and animal density of animals per square kilometers. Thus, units would need to be converted to use Equations 2a,b.

[46] This equation matches Equation 3 from Sivle et al. (2014), but is written in a simpler manner.

4. Exposure threshold (inverse relationship: as the exposure threshold decreases, the safe distance increases or vice versa).

The action proponent is responsible for providing information on factors one through three, while factor four is the updated PTS onset acoustic threshold level (expressed as SEL_{cum} metric) provided within the Guidance.

For the safe distance approach to applicable to a broad range of activities, the following assumptions must be made:

- Action proponents that are unable to apply full auditory weighting functions will rely on alternative acoustic threshold levels. This will create larger isopleths compared to action proponents capable of fully applying auditory weighting functions.

- The movement of the source is simple (i.e., source moves at a constant speed and in a constant direction). This assumption is appropriate for sources that are expected to move much faster than the receiver does. Caution should be applied if the source has the potential to move in a manner where the same group of receivers could be exposed to multiple passes from the source.

- Receivers are considered stationary and assumed to not move up or down within the water column). There is no avoidance and the receiver accumulates sound via one pass of the source (i.e., receiver is not exposed to multiple passes from the source). Because the safe distance only examines one pass of the source relative to receiver, this method is essentially time-independent.

    - These assumptions are appropriate for sources that are expected to move much faster than the receiver does. Furthermore, assuming receivers do not avoid the source or change position vertically or horizontally in the water column will result in more exposures exceeding the acoustic threshold levels compared to those receivers that would avoid or naturally change positions in the water column over time. Caution should be applied if the receiver has the potential to follow or move with the sound source.

- Distance between "pulses" for intermittent sources is small compared with safe distance, and the distance between "pulses" for intermittent sources is consistent. This assumption is appropriate for intermittent sources with a predictable duty cycle. If the duty cycle decreases, the safe distance will become larger, while if the duty cycle increases, it will become smaller.

- The transmission loss associated with propagation is simple (i.e., the safe distance approach uses spherical spreading: 20 log R, with no absorption). NOAA recognizes that this might not be appropriate for all activities, especially those occurring in

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shallow water (i.e., sound could propagate further than predicted by this model). Thus, modifications to safe distances predicted may be necessary in these situations.

Despite these assumptions, the safe distance approach offers a better approximation of the source-receiver distance over space and time for various mobile sources than choosing a set accumulation period for all sources, which assumes a fixed source-receiver distance over that time.

Ainslie and Von Benda-Beckmann (2013) investigated the effect various factors had on the derivation of safe distances and found exposures were highest for stationary receivers in the path of a source, compared to mobile receivers swimming away from the source. However, the authors did acknowledge, if the receivers actively swam toward the source, cumulative exposure would increase. Uncertainty associated with safe distances was found to be primarily driven by the exposure threshold (i.e., Acoustic Guidance's acoustic threshold levels). Increasing duty cycle of the source or reducing speed (either source or receiver) will result in an increased safe distance (Sivle et al. 2014)

NOAA has provided a spreadsheet **(TO BE RELEASED WITH THE FINAL GUIDANCE)** to help action proponents use this methodology to determine isopleths for PTS onset associated with their activity (http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm).

Note: NOAA's alternative methods apply only to acoustic threshold levels in the SEL_{cum} metric. NOAA assumes action proponents should be able to perform exposure modeling using acoustic threshold levels expressed using the peak pressure metric (i.e., methodology is similar to that used with NOAA previous thresholds but with a different metric), and reminds action proponents since the Guidance presents dual thresholds, they must evaluate thresholds using both metrics.

3.2.2 Stationary Sources: 24-h Accumulated Isopleth

If there is enough information to accurately predict the travel speed of a receiver past a stationary sound source (including the assumption that the receiver swims on a straight trajectory past the source), then the safe distance approach can be modified for stationary sources (i.e., speed of the source is replaced by speed of the receiver). However, NOAA acknowledges that characteristics of the receiver are less predictable compared to those of the source (i.e., velocity and travel path), which is why the safe distance approach may not be appropriate for stationary sources and an alternate method is provided below.

An alternative approach is to calculate the accumulated isopleth associated with a stationary sound source within a 24-h period. For example, if vibratory pile driving was expected to occur over ten hours within a 24-h period, then the isopleth would be calculated by adding area with each second the source is producing sound. This is a highly conservative means of calculating an isopleth because it assumes that animals on the edge of the isopleth (in order

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to exceed a threshold) will remain there for the entire time of the activity. For most stationary, non-impulsive sources (e.g., vibratory pile driving, drilling, dynamic positioning) accumulating over the entire period the source is producing sound, within a 24-h period, typically results in relatively small isopleths (i.e., most of these sources have lower source levels compared to impulsive sources).

For stationary, impulsive sources with high source levels (i.e., impulsive pile driving associated with large piles, stationary airguns associated with vertical seismic profiling (VSPs), and large explosives) accumulating over a 24-h period, depending on how many strikes or shots occur, could lead to unrealistically large isopleths associated with PTS onset. For these situations, NOAA suggests the consideration of applying a transition range (i.e., transitioning from the use of impulsive to non-impulsive acoustic threshold levels) to produce more representative isopleths (see main document, Section 2.3.1).

NOAA has provided a spreadsheet **(TO BE RELEASED WITH THE FINAL GUIDANCE)** to help action proponents wanting to use this methodology to determine isopleths for PTS onset associated with their activity (http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm).

Note: NOAA's alternative methods apply only to acoustic threshold levels in the SEL_{cum} metric. NOAA assumes action proponents should be able to perform exposure modeling using acoustic threshold levels expressed using the peak pressure metric (i.e., methodology is similar to that used with NOAA previous thresholds but with a different metric) and reminds action proponents since the Guidance presents dual thresholds, they must evaluate thresholds using both metrics.

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APPENDIX F: GLOSSARY

Accumulation period: The amount of time a sound accumulates for the SEL_{cum} metric.

Acoustic threshold level: An acoustic threshold in this document identifies the level of sound after which exceeded NOAA anticipates (after evaluating and interpreting all available science) a change in auditory sensitivity (temporary or permanent threshold shift).

Ambient noise: All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI 1994).

Animat: A simulated marine mammal.

Anthropogenic: Originating (caused or produced by) from human activity.

Audible: Heard or capable of being heard.

Audiogram: A graph depicting hearing threshold level as a function of frequency (ANSI 1995; Yost 2007) (Figure E1).

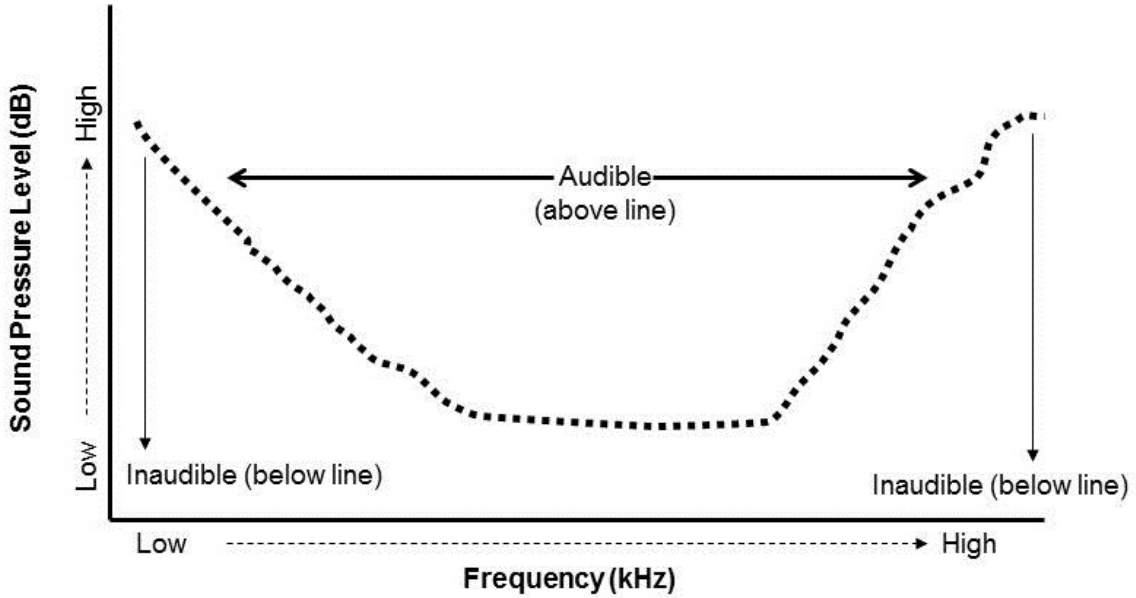


Figure F1. Example audiogram.

Auditory bulla: The ear bone in odontocetes that houses the middle ear structure (Perrin et al. 2009).

Auditory weighting function (frequency-weighting function): Auditory weighting functions take into account what is known about marine mammal hearing sensitivity and

susceptibility to noise-induced hearing loss and can be applied to a sound-level measurement to account for frequency-dependent hearing (i.e.,. an expression of relative loudness as perceived by the ear)(Southall et al. 2007; Finneran and Jenkins 2012) (see Figures 1-3). Similar to OSHA (2013), marine mammal auditory weighting functions in this document are used to reflect the risk of noise exposure on hearing and not necessarily capture the most sensitive hearing range of every member of the functional hearing group.

Background noise: Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI 2013).

Band-pass filter: A filter that passes frequencies within a defined range without reducing amplitude and attenuates frequencies outside that defined range (Yost 2007).

Bandwidth: Bandwidth (Hz or kHz) is the range of frequencies over which a sound occurs (ANSI 2005). Broadband refers to a source that produces sound over a broad range of frequencies (for example, seismic airguns), while narrowband or tonal sources produce sounds over a more narrow frequency range, typically with a spectrum having a localized a peak in amplitude (for example, sonar) (ANSI 1986; ANSI 2005).

Broadband: See "bandwidth".

Cetacean: Any number of the order Cetacea of aquatic, mostly marine mammals that includes whales, dolphins, porpoises, and related forms; among other attributes they have a long tail that ends in two transverse flukes (Perrin et al. 2009).

Cochlea: Spirally coiled, tapered cavity within the temporal bone, which contains the receptor organs essential to hearing (ANSI 1995). For cetaceans, based on cochlear measurements two cochlea types have been described for echolocating odontocetes (type I and II) and one cochlea type for mysticetes (type M). Cochlea type I is found in species like the harbor porpoise and Amazon river dolphin, which produce high-frequency echolocation signals. Cochlea type II is found in species producing lower frequency echolocation signals (Ketten 1992).

Cognition: Cognition is all stages of information processing from reception by sensory organs to decisions executed by the brain (Dukas 2004).

Continuous sound: A sound whose sound pressure level remains above ambient sound during the observation period (ANSI 2005).

Crest factor: Ten times the logarithm to the base ten of the square of the wideband peak amplitude of a signal to the time-mean-square amplitude over a stated time period (ANSI 1995).

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Critical level: The level at which damage switches from being primarily metabolic to more mechanical; e.g., short duration of impulse can be less than the ear's integration time, leading for the potential to damage beyond level the ear can perceive (Akay 1978).

Cumulative sound exposure level (SEL_{cum}; equivalent to the ANSI abbreviation of L_E): Level of acoustic energy accumulated over a given period of time or event (EPA 1982) or specifically, ten times the logarithm to the base ten of the ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event to the squared reference pressure (ANSI 1995; ANSI 2013). Note: SEL typically is defined with a reference time of one second. However, NOAA intends that cumulative SEL account for accumulation over the recommended baseline accumulation period.

Deafness: A condition caused by a hearing loss that results in the inability to use auditory information effectively for communication or other daily activities (ANSI 1995).

Decibel (dB): One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI 2013).

dB/decade: This unit is typically used to describe roll-off, where a decade is a 10-times increase in frequency (roll-off can also be described as decibels per octave, where an octave is 2-times increase in frequency)

Duty cycle: On/off cycle time or proportion of time signal is active (calculated by: pulse length/interpulse interval). A continuous sound has a duty cycle of 1 or 100%.

Effective quiet: The maximum sound pressure level that will fail to produce any significant threshold shift in hearing despite duration of exposure and amount of accumulation (Ward et al. 1976; Ward 1991).

Endangered Species Act (ESA): The Endangered Species Act of 1973 (ESA) (16. U.S.C 1531 et. seq.)provides for the conservation of species that are endangered or threatened throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend.

NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the ESA.

Equal Energy Hypothesis (EEH): Assumption that sounds of equal energy produce the equal risk for hearing loss (i.e., if the cumulative energy of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks to a shorter duration exposure from a higher level source) (Henderson et al. 1991).

Equal-loudness contour: A curve or curves that show, as a function of frequency, the sound pressure level required to cause a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI 2013).

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Fitness: Survival and lifetime reproductive success of an individual.

Frequency: The number of periods occurring over a unit of time (unless otherwise stated, cycles per second or hertz) (Yost 2007).

Functional hearing range: There is no standard definition of functional hearing arrange currently available. "Functional" refers to the range of frequencies a group hears without incorporating non-acoustic mechanisms (Wartzok and Ketten 1999). Southall et al. 2007 defined upper and lower limits of the functional hearing range as ~60-70 dB above the best hearing sensitivity (based on human and mammalian definition of 60 dB[47]). The guidance separates marine mammals under NOAA's jurisdiction into five functional hearing groups: low-frequency cetacean, mid-frequency cetacean, high-frequency cetacean, and phocid and otariid pinnipeds.

Harmonic: A sinusoidal quantity that has a frequency which is and integral multiple of the frequency of the periodic quantity to which it is related (ANSI 2013).

Hearing loss growth rates: The rate of threshold shift increase (or growth) as decibel level or exposure duration increase (expressed in dB of temporary threshold shift/dB of noise).Growth rates of threshold shifts are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran 2011). Typically in terrestrial mammals, the magnitude of a threshold shift increases with increasing duration or level of exposure, until it becomes asymptotic (growth rate begins to level or the upper limit of TTS; Mills et al. 1979; Clark et al. 1987; Laroche et al. 1989; Yost 2007).

Hertz (Hz): Unit of frequency corresponding to the number of cycles per second. One hertz corresponds to one cycle per second.

High-frequency cetacean: See "functional hearing group".

Impulsive sound: Sound sources that produce sounds that are transient, brief (less than 1 second), broadband, and typically consist of high peak pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event. Examples of impulsive sound sources include: explosives, seismic airguns, and impact pile drivers.

Information Quality Guidelines (IQG): Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554), directs the Office of Management and Budget (OMB) to issue government-wide guidelines (OMB Guidelines) that "provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information (including

[47] In humans, functional hearing is typically defined as frequencies at a threshold of 60 to 70 dB and below (Masterson et al. 1969; Wartzok and Ketten 1999), with normal hearing in the most sensitive hearing range considered 0 dB (i.e., 60 to 70 dB above best hearing sensitivity).

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statistical information) disseminated by federal agencies." OMB issued guidelines directing each federal agency to issue its own guidelines.
NOAA's Information Quality Guidelines can be viewed at:
http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html

Integration time (of the ear): For a signal to be detected by the ear, it must have some critical amount of energy. The process of summing the power to generate the required energy is completed over a particular integration time. If the duration of a signal is less than the integration time required for detection, the power of the signal must be increased for it to be detected by the ear (Yost 2007).

Intermittent sound: Interrupted levels of low or no sound (NIOSH 1998) or bursts of sounds separated by silent periods (Richardson and Malme 1993). Typically, intermittent sounds have a more regular (predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle).

Isopleth: A line drawn through all points having the same numerical value. In the case of sound, the line has equal sound pressure levels.

Kurtosis: Statistical quantity that represents the impulsiveness ("peakedness") of the event; specifically the ratio of fourth- order central moment to the squared second-order central moment (Hamernik et al. 2003; Davis et al. 2009).

Linear interpolation: A method of constructing new data points within the range of a discrete set of known data points, with linear interpolation being a straight line between two points derived by the following equation:

$$y = y_1 + (x - x_1)\frac{y_2 - y_1}{x_2 - x_1}$$ **Equation E1**

Low-frequency cetacean: See "functional hearing group".

Marine Mammal Protection Act (MMPA): The Marine Mammal Protection Act (MMPA) (16. U.S.C. 1361 et. seq.)was enacted on October 21, 1972 and MMPA prohibits, with certain exceptions, the "take" of marine mammals in U.S. waters and by U.S. citizens on the high seas, and the importation of marine mammals and marine mammal products into the United States. NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the MMPA.

Masking: Obscuring of sounds of interest by interfering sounds, generally of the similar frequencies (Richardson et al. 1995).

Mean-squared error (MSE): In statistics, this measures the average of the squares of the "errors", that is, the difference between the estimator and what is estimated.

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Mid-frequency cetacean: See "functional hearing group".

Multipath propagation: This phenomenon occurs whenever there is more than one propagation path between the source and receiver (i.e., direct path and paths from reflections off the surface and bottom or reflections within a surface or deep-ocean duct; Urick 1983).

Mysticete: The toothless or baleen (whalebone) whales, including the rorquals, gray whale, and right whale; the suborder of whales that includes those that bulk feed and cannot echolocate (Perrin et al. 2009).

Narrowband: See "bandwidth".

National Marine Sanctuaries Act (NMSA): The National Marine Sanctuaries Act(16 U.S.C. 1431 et. seq.) authorizes the Secretary of Commerce to designate and protect areas of the marine environment with special national significance due to their conservation, recreational, ecological, historical, scientific, cultural, archeological, educational, or esthetic qualities as national marine sanctuaries. Day-to-day management of national marine sanctuaries has been delegated by the Secretary of Commerce to NOAA's Office of National Marine Sanctuaries.

National Standard 2 (NS2): The Magnuson-Stevens Fishery Conservation and Management Act (MSA) (16 U.S.C. 1801 et. seq.) is the principal law governing marine fisheries in the U.S. and includes ten National Standards to guide fishery conservation and management. One of these standards, referred to as National Standard 2 (NS2), guides scientific integrity and states that "(fishery) conservation and management measures shall be based upon the best scientific information available."

Non-impulsive sound: Sound sources that produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak pressure with rapid rise time that impulsive sounds do. Examples of non-impulsive sound sources include: marine vessels, machinery operations/construction (e.g., drilling), certain active sonar (e.g. tactical), and vibratory pile drivers.

Octave: The interval between two sounds having a basic frequency ratio of two (Yost 2007). For example, one octave above 400 Hz is 800 Hz. One octave below 400 Hz is 200 Hz.

Odontocete: The toothed whales, including sperm and killer whales, belugas, narwhals, dolphins and porpoises; the suborder of whales including those able to echolocate (Perrin et al. 2009).

Otariid: The eared seals (sea lions and fur seals), which use their foreflippers for propulsion (Perrin et al. 2009).

Peak-to-peak sound pressure level (dB_{p-p}; re: 1 µPa): Signals that have a distinctive signature comprising a clear pressure minimum immediately following a clear maximum or

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vice-versa (TNO 2011).

Peak pressure sound pressure level (dB_{peak}; re: 1 µPa; equivalent to the ANSI abbreviation of L_{pk}**):** The greatest absolute instantaneous sound pressure within a specified time interval (ANSI 1986; ANSI 2013).

Perception: Perception is the translation of environmental signals to neuronal representations (Dukas 2004).

Permanent threshold shift (PTS): A permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of permanent threshold shift is customarily expressed in decibels (ANSI 1995; Yost 2007). Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

Phocid: A family group within the pinnipeds that includes all of the "true" seals (i.e. the "earless" species). Generally used to refer to all recent pinnipeds that are more closely related to *Phoca* than to otariids or the walrus (Perrin et al. 2009).

Pinniped: Seals, sea lions and fur seals (Perrin et al. 2009).

Primary pulse: Primary pulses or first arrivals, associated with sound propagation, are those components independent of interacting with properties of the sea floor and/or subsurface and independent of bubble energy (Breitzke et al. 2008). The duration of the primary pulse consists of the time between 5% and 95% of a pulse's total cumulative energy (Madsen 2005).

Received Level (RL): The level of sound measured at the receiver.

Reference pressure: See sound pressure level.

Rise time: The time interval a signal takes to rise from 10% to 90% of its highest peak (ANSI 1986; ANSI 2013).

Roll-off: Change in weighting function amplitude (-dB) with changing frequency.

Root-mean-square sound pressure level (dB_{rms}; re: 1 µPa): The square root of the average of the square of the pressure of the sound signal over a given duration (ANSI 1986; ANSI 2013).

Sensation level (dB): The pressure level of a sound above the hearing threshold for an individual or group of individuals (ANSI 1995; Yost 2007).

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Sound Exposure Level (SEL): A measure of sound level that takes into account the duration of the signal. Ten times the logarithm to the base 10 of the ration of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event to the product of the squared reference sound pressure (1 μPa in water) and reference duration of one second (ANSI 2013).

Sound Pressure Level (SPL): A measure of sound level that represents only the pressure component of sound. Ten times the logarithm to the base 10 of the ratio of time-mean-square pressure of a sound in a stated frequency band to the square of the reference pressure (1 μPa in water). Note: A sound pressure level with reference to a pressure of 1 μPa in water in numerically ≈ 26 decibels greater than the sound pressure level for the same sound pressure with a reference to 20 μPa (reference pressure in gasses) (ANSI 2013).

Source Level (SL): The level of a sound measured in the far field and scaled to a standard reference distance (1 meter) away from the source (Richardson et al. 1995; ANSI 2013).

Spatial: Of or relating to space or area.

Spectral/spectrum: Of or relating to frequency component(s) of sound. The spectrum of a function of time is a description of its resolution into components (frequency, amplitude, etc.). The spectrum level of a signal at a particular frequency is the level of that part of the signal contained within a band of unit width and centered at a particular frequency (Yost 2007).

Spectral density levels: Level of the limit, as the width of the frequency band approaches zero, of the quotient of a specified power-like quantity distributed within a frequency band, by the width of the band (ANSI 2013).

Temporal: Of or relating to time.

Temporary threshold shift (TTS): A temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of temporary threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007). Based on data from cetacean TTS measurements (see Southall et al. 2007 for a review), a TTS of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation in a subject's normal hearing ability (Schlundt et al. 2000; Finneran et al. 2000; Finneran et al. 2002).

Threshold (of audibility): The threshold of audibility (auditory threshold) for a specified signal is the minimum effective sound pressure level of the signal that is capable of evoking an auditory sensation in a specified fraction of trials (either physiological or behavioral) (Yost 2007).

Threshold shift: A change, usually an increase, in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established

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reference level. The amount of threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007).

Tone: A sound wave capable of exciting an auditory sensation having pitch. A pure tone is a sound sensation characterized by a single pitch (one frequency). A complex tone is a sound sensation characterized by more than one pitch (more than one frequency) (ANSI 2013).

Transmission (or propagation) loss: Reduction in magnitude of some characteristic of a signal between two stated points in a transmission system (for example the reduction in the magnitude of a signal between a source and a receiver) (ANSI 2013).

Uncertainty: Lack of knowledge about a parameter's true value (Bogen and Spears 1987; Cohen et al. 1996).

Variability: Differences between members of the populations that affects the magnitude of risk to an individual (Bogen and Spears 1987; Cohen et al. 1996; Gedamke et al. 2011).

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