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

Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-OPR-55
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Office of Protected Resources
National Marine Fisheries Service
Silver Spring, MD 20910

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California sea lion (*Zalophus californianus*), Otariid pinniped Photo: Sharon Melin (NOAA)

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

a	Low-frequency exponent
ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
AM	Amplitude Modulated
ANSI	American National Standards Institute
b	High-frequency exponent
C	Weighting function gain (dB)
CT	Computerized Tomography
D	Duty Cycle
dB	Decibel
PK	Peak sound level
DPOAE	Distortion product otoacoustic emission
$E(f)$	Exposure function
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	hour
HF	High-frequency
HISA	Highly Influential Scientific Assessment
Hz	Hertz
ISI	Influential Scientific Information
IQG	Information Quality Guidelines
ITA	Incidental Take Authorizations
K	Exposure function gain (dB)
kHz	Kilohertz
LF	Low-frequency
L_{pk}	Peak sound pressure level
$L_{\mathrm{pk,flat}}$	Peak sound pressure level (unweighted)
$L_{\mathrm{E,24h}}$	Sound exposure level, cumulative 24h
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
NIHL	Noise-induced Hearing Loss
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
OPR	Office of Protected Resources
OSHA	Occupational Safety and Health Administration
OW	Otariids in water
p_0	Sound Pressure Level
Pa	Pascals

π	pi
PTS	Permanent Threshold Shift
PW	Phocids in water
R	Range
R_0	"Safe Distance"
R^2	Goodness of fit
RMS	Root Mean Square
S	Source Factor
S_E	Energy Source Factor
s	Seconds
s	Distance from source
s_0	Slope
SEL	Sound exposure level
SEL_{cum}	Cumulative sound exposure level
SL	Source Level
SL_E	Energy Source Level
s_0	Slope (dB/decade)
SPL	Sound Pressure Level
SSC-PAC	SPAWAR Systems Center Pacific
τ	1/repetition rate
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 (transit speed)
$W(f)$	Weighting function
WFA	Weighting factor adjustments

EXECUTIVE SUMMARY

This document provides technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction of the National Marine Fisheries Service (NMFS) and was completed in collaboration with the National Ocean Service (NOS), Office of National Marine Sanctuaries. Specifically, it identifies the received levels, or acoustic thresholds, at 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 NMFS has presented this information in a single, comprehensive document. This Technical Guidance is intended for use by NMFS analysts/managers and other relevant action proponents/stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in potential impacts to marine mammal hearing via acoustic exposure. This document outlines the development of NMFS' acoustic thresholds and describes how they will be updated in the future.

NMFS has compiled, interpreted, and synthesized the scientific literature, including a recent Technical Report by Dr. James Finneran (U.S. Navy-SPAWAR Systems Center Pacific (SSC-PAC)) (Finneran 2016; Appendix A of this Technical Guidance), to produce acoustic thresholds for onset of temporary (TTS) and permanent threshold shifts (PTS) (Table ES2) that update those currently in use by NMFS. Updates include a protocol for estimating PTS onset acoustic thresholds for impulsive (e.g., airguns, impact pile drivers) and non-impulsive (e.g., tactical sonar, vibratory pile drivers) sound sources, the formation of marine mammal hearing groups (low- (LF), mid- (MF), and high- (HF) frequency cetaceans, and otariid (OW) and phocid (PW) pinnipeds; Table ES1), and the incorporation of marine mammal auditory weighting functions (Figures ES1 and ES2) into the derivation of PTS acoustic thresholds. These acoustic thresholds are presented using dual metrics of cumulative sound exposure level (SEL_{cum}) and peak sound level (PK) for impulsive sounds and SEL_{cum} for non-impulsive sounds.

While the Technical Guidance's acoustic thresholds are more complex than those used to date in most cases by NMFS, 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 generally or directly compare the updated acoustic thresholds presented in this document with the thresholds they will replace because outcomes will depend on project-specific specifications. NMFS recognizes that the implementation of marine mammal weighting functions and the SEL_{cum} metric represent new factors for consideration, which may extend beyond the capabilities of some action proponents. Thus, NMFS has developed alternative tools for those who cannot fully incorporate these factors (See Appendix D and Technical Guidance's companion User Spreadsheet[1]).

These updated PTS acoustic thresholds do not represent the entirety of a comprehensive analysis of the effects of a proposed action, but rather serve as one tool (along with, e.g.,

[1] Located at: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

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 and make the relevant findings required by NOAA's various statutes.

This Technical Guidance is classified as a Highly Influential Scientific Assessment (HISA) by the President's Office of Management and Budget (OMB). 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 Technical Guidance, are within this document (Appendix C).

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. NMFS' updated acoustic thresholds for onset of PTS for marine mammals exposed to underwater sound are presented in Section II. NMFS' plan for periodically updating acoustic thresholds is presented in Section III. More details on the development of acoustic thresholds, the peer review and public comment process, research recommendations, alternative methodology, and a glossary of acoustic terms are found in the appendices.

The following Tables and Figures summarize the three main aspects of the Technical Guidance: 1) Marine mammal hearing groups (Table ES1), 2) Marine mammal auditory weighting functions (Figures ES1 and ES2; Table ES2), and PTS onset acoustic thresholds (Table ES3).

Table ES1: Marine mammal hearing groups.

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 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*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

***** Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

Table ES2: Summary of weighting and exposure function parameters.*

Hearing Group	*a*	*b*	*f1* (kHz)	*f2* (kHz)	*C* (dB)	*K* (dB)
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179
Mid-frequency (MF) cetaceans	1.6	2	8.8	110	1.20	177
High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75	180
Otariid pinnipeds (OW) (underwater)	2.0	2	0.94	25	0.64	198

* Equations associated with Technical Guidance's weighting (*W(f)*) and exposure functions (*E(f)*):

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

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

Table ES3: Summary of PTS onset acoustic thresholds.

	PTS Onset Acoustic Thresholds* **(Received Level)**	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{pk,flat}$: 219 dB $L_{E,LF,24h}$: 183 dB	*Cell 2* $L_{E,LF,24h}$: 199 dB
Mid-Frequency (MF) Cetaceans	*Cell 3* $L_{pk,flat}$: 230 dB $L_{E,MF,24h}$: 185 dB	*Cell 4* $L_{E,MF,24h}$: 198 dB
High-Frequency (HF) Cetaceans	*Cell 5* $L_{pk,flat}$: 202 dB $L_{E,HF,24h}$: 155 dB	*Cell 6* $L_{E,HF,24h}$: 173 dB
Phocid Pinnipeds (PW) (Underwater)	*Cell 7* $L_{pk,flat}$: 218 dB $L_{E,PW,24h}$: 185 dB	*Cell 8* $L_{E,PW,24h}$: 201 dB
Otariid Pinnipeds (OW) (Underwater)	*Cell 9* $L_{pk,flat}$: 232 dB $L_{E,OW,24h}$: 203 dB	*Cell 10* $L_{E,OW,24h}$: 219 dB

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

Note: Peak sound pressure (L_{pk}) has a reference value of 1 μPa, and cumulative sound exposure level (L_E) has a reference value of 1μPa^{2}s. In this Table, thresholds are abbreviated to reflect American National Standards Institute standards (ANSI 2013). However, peak sound pressure is defined by ANSI as incorporating frequency weighting, which is not the intent for this Technical Guidance. Hence, the subscript "flat" is being included to indicate peak sound pressure should be flat weighted or unweighted within the generalized hearing range. The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these acoustic thresholds will be exceeded.

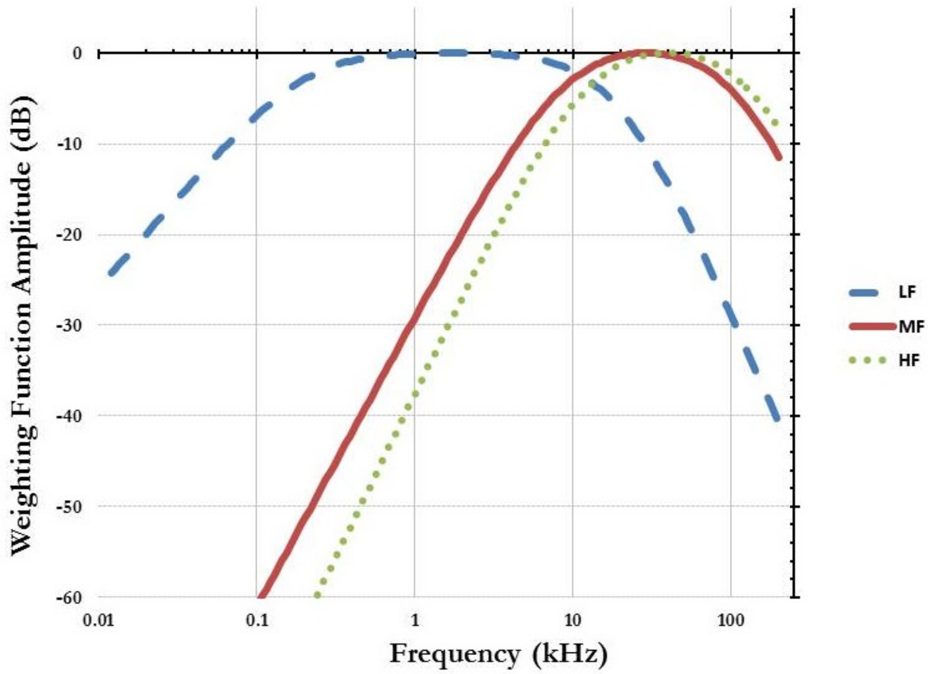

Figure ES1: **Auditory weighting functions for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans.**

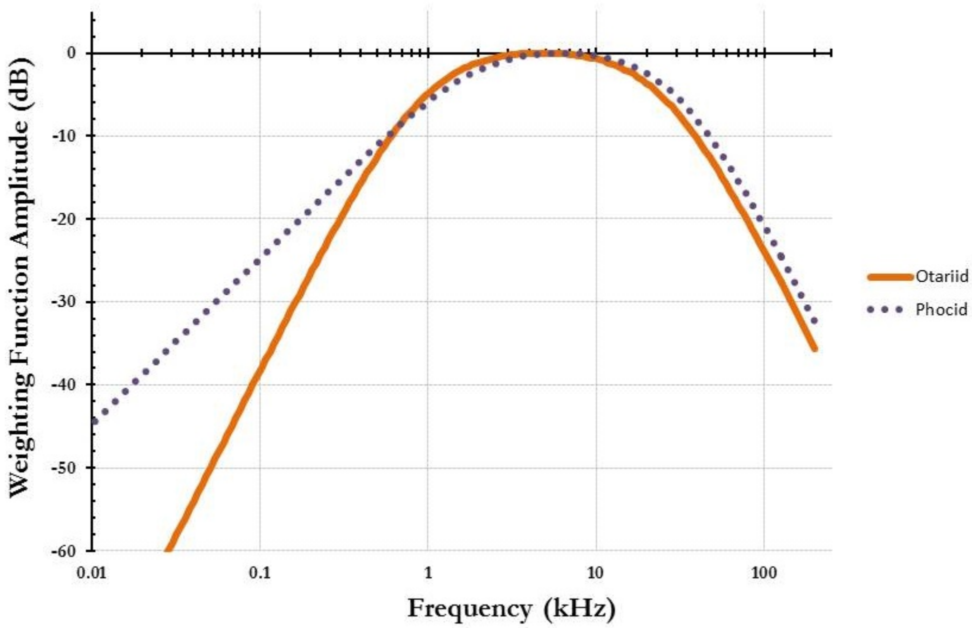

Figure ES2: **Underwater auditory weighting functions for otariid (OW) and phocid (PW) pinnipeds.**

TECHNICAL GUIDANCE FOR ASSESSING THE EFFECTS OF ANTHROPOGENIC SOUND ON MARINE MAMMAL HEARING

UNDERWATER ACOUSTIC THRESHOLDS FOR ONSET OF PERMANENT AND TEMPORARY THRESHOLD SHIFTS

I. INTRODUCTION

This document provides technical guidance[2] for assessing the effects of anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction[3] of the National Marine Fisheries Service (NMFS) and was completed in collaboration[4] with the National Ocean Service (NOS), Office of National Marine Sanctuaries. Specifically, it identifies the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity for acute, incidental exposure to all underwater anthropogenic sound sources. This Technical Guidance is intended for use by NMFS analysts/ managers and other relevant action proponents/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 NMFS' updated acoustic thresholds, describing in detail threshold development (via Appendix A), and how they will be revised and updated in the future.

The acoustic thresholds presented in this document do not represent the entirety of an effects analysis, but rather serve as one tool among others (e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the effects of any particular type of impact on an individual's fitness, population assessments, etc.), to help evaluate the effects of a proposed action and make findings required by NOAA's various statutes.

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[2] This Technical Guidance does not create or confer any rights for or on any person, or operate to bind the public. An alternative approach that has undergone independent peer review 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 auditory impact for the project being evaluated; and if NMFS determines the approach satisfies the requirements of the applicable statutes and regulations.

[3] 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 (USFWS) jurisdiction (e.g., walrus, polar bears, West Indian manatees, sea otters). However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water groups, including sirenian datasets (Gerstein et al. 1999; Mann et al. 2009), to derive composite audiogram parameters and threshold of best hearing for LF cetaceans (see Appendix A_1). Additionally, audiogram data from a single Pacific walrus (Kastelein et al. 2002) and a single sea otter (Ghoul and Reichmuth 2014) were included in the derivation of the composite audiogram for OW pinnipeds.

[4] Draft versions of this document referred to it as a joint document by NOS and NMFS. However, this final version more accurately identifies it as a NMFS-directed effort/document that was completed in association with NOS.

Note: This document does not directly address mitigation and monitoring measures[5] that may be associated with particular activities, nor does it set forth requirements to conduct sound source verification studies.

This Technical Guidance is classified as a Highly Influential Scientific Assessment (HISA)[6] 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 Technical Guidance underwent three independent peer reviews (details provided in Appendix C). NMFS also sought informal input from key federal agencies regarding various aspects of this document in early stages of its development.

1.1 NEED FOR TECHNICAL GUIDANCE AND UPDATED UNDERWATER ACOUSTIC THRESHOLDS

Prior to this Technical Guidance, NMFS has primarily relied on two generic acoustic thresholds for assessing auditory impacts (i.e., permanent threshold shift [PTS] onset) for most underwater sound sources: one for cetaceans (RMS SPL 180 dB), and one for pinnipeds (RMS SPL 190 dB). These generic thresholds were developed in the late 1990s using the best information available (e.g., NOAA 1998; HESS 1999). Other sound sources, like tactical sonar and underwater explosives, have relied on more recently developed acoustic thresholds (e.g., Finneran and Jenkins 2012; NOAA 2014). Since the adoption of these original generic thresholds, the understanding of the effects of noise on marine mammal hearing has greatly advanced (e.g., Southall et al. 2007; Finneran 2015; Erbe et al. 2016) making it necessary to more comprehensively examine the current state of science and the acoustic thresholds.

For this document, NMFS has compiled, interpreted, and synthesized the scientific literature on the impacts of sound on marine mammal hearing, including the recent Finneran Technical Report (Finneran 2016; Appendix A of this Technical Guidance), to produce updated underwater acoustic thresholds for the onset of TTS and PTS. These acoustic thresholds update those currently in use by NMFS estimating PTS onset from all sources, as well as those currently in use for estimating TTS[7] onset from underwater detonations. The

[5] Mitigation and monitoring requirements associated with an MMPA authorization or ESA consultation or permit are independent management decisions made in the context of the proposed activity and comprehensive effects analysis, and are beyond the scope of the Technical Guidance. NMFS acknowledges exclusion zones and monitoring zones often correspond to acoustic thresholds but that is not a legal requirement, and the updated thresholds may make such a simple correlation more challenging. The Technical Guidance can be used to inform the development of mitigation or monitoring.

[6] 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). The decision to designate the Technical Guidance as a HISA was based on the latter part of OMB's definition (i.e., precedent-setting).

[7] TTS onset thresholds are found in Appendix A, Table A10.

Technical Guidance's acoustic thresholds are more complex reflecting the current state of scientific knowledge regarding marine mammal hearing and the characteristics of sound that have the potential to impact marine mammal hearing sensitivity.

This is the first time NMFS has presented this information in a single, comprehensive document, which can be used by NMFS analysts/managers and other relevant action proponents/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.

1.1.1 Acoustic thresholds within the Context of an Effects Analysis

The Technical Guidance's acoustic thresholds do not represent the entirety of an effects analysis, but rather serve as one tool to help evaluate the effects of sound produced during a proposed action on marine mammals and make findings required by NOAA's various statutes. In a regulatory context, NMFS uses acoustic thresholds to help assess and quantify "take" and to conduct more comprehensive effects analyses under several statutes.

Specifically, the Technical Guidance 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 and types of takes of marine mammals. This document only addresses acoustic thresholds for auditory impact (i.e., does not address or make recommendations associated with sound propagation or marine mammal occurrence or density).

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 (2016) acknowledged the inherent data limitations when making 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 Finneran (2016) and Southall et al. (2007) 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. The Technical Guidance articulates where NMFS has faced such uncertainty and variability in the development of its acoustic thresholds.

1.2.1 Assessment Framework

NMFS' approach applies a set of assumptions to address 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 thresholds 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 individual level) but is also scientifically based (i.e., taxonomy, hearing group). As new data become available for more species, this approach can be reevaluated. NMFS recognizes that additional applicable data may become available to better address many of these issues (e.g., uncertainty, surrogate species, etc.).[8] As these new data become available, NMFS has an approach for updating this document (see Section III).

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[9] (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). Further, the IQG stipulate that "To the degree that the agency action is based on science, NMFS 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 for National Standard 2 (NS2) in section 301 of the Magnuson-Stevens Fishery Conservation and Management Act, which states that "Conservation and management measures shall be based upon the best scientific information available" (NOAA 2013). 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.[10] 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. NMFS 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.

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[8] NMFS is aware that the authors of Southall et al. (2007) are in the process of updating their original publication and recognizes that when this updated publication becomes available, it may suggest alternative means for predicting an auditory weighting function and acoustic thresholds for LF cetaceans. Accordingly, NMFS may re-evaluate our methodology for LF cetaceans when this updated Southall et al. publication becomes available.

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

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

II. NMFS' ACOUSTIC THRESHOLDS FOR ONSET OF PERMANENT THRESHOLD SHIFTS IN MARINE MAMMALS

The Technical Guidance advances NMFS' assessment ability based upon the compilation, interpretation, and synthesis of the scientific literature. This document provides thresholds for the onset of PTS based on characteristics defined at the acoustic source. No direct measurements of marine mammal PTS have been published; PTS onset acoustic thresholds have been extrapolated from marine mammal TTS measurements (i.e., using growth rates from terrestrial and marine mammal data). PTS onset acoustic thresholds, for all sound sources are divided into two broad categories: 1) impulsive and 2) non-impulsive. Acoustic thresholds are also presented as dual metric acoustic thresholds using cumulative sound exposure level ($SEL_{cum,}$) and peak sound pressure (PK) metrics for impulsive sounds. As dual metrics, NMFS considers onset of PTS to have occurred when either one of the two metrics is exceeded. For non-impulsive sounds, thresholds are provided using the SEL_{cum} metric. Additionally, to account for the fact that different species groups use and hear sound differently, marine mammals are sub-divided into five broad hearing groups (i.e., LF, MF, HF, PW, and OW) and acoustic thresholds in the SEL_{cum} metric incorporate auditory weighting functions.

2.1 MARINE MAMMAL 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 odontocete and pinniped species[11] (see reviews in Southall et al. 2007; Erbe et al. 2016; Finneran 2016). Direct measurements of mysticete hearing are lacking.[12] Thus, hearing predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001; Parks et al. 2007; Tubelli et al. 2012; Cranford and Krysl 2015[13]); vocalizations[14] (see reviews in Richardson et al. 1995; Wartzok and Ketten 1999; Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990; see review in Reichmuth 2007).

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

[12] There was an unsuccessful attempt to directly measure hearing in a stranded gray whale calf by Ridgway and Carder 2001.

[13] <u>Note</u>: The modeling of Cranford and Krsyl (2015) predicts that the primary mechanism for hearing in LF cetaceans is bone conduction. Additionally, this predictive model was based on the skull geometry of a newborn fin whale.

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

To better reflect marine mammal hearing capabilities, Southall et al. (2007) recommended that marine mammals be divided into hearing groups (Table 1). NMFS made the following modifications to the hearing groups proposed in Southall et al. (2007)[15]:

- <u>Division of pinnipeds into PW and OW hearing groups</u>: NMFS 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. 2009a; Reichmuth et al. 2013). Phocid ears are anatomically distinct from otariid ears in that phocids have larger, more dense middle ear ossicles, inflated auditory bulla, and larger sections 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).

- <u>Recategorizatin of hourglass (*Lagenorhynchus cruciger*) and Peale's (*L. australis*) dolphins from MF cetacean to HF cetacean hearing group:</u>[16] Echolocation data (Kyhn et al. 2009; Kyhn et al. 2010; Tougaard and Kyhn. 2010) indicate that the hourglass and Peale's dolphin 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, based on this information, NMFS has decided to move these two species from MF cetaceans to HF cetaceans.

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[15] NMFS considered dividing LF cetaceans into two separate groups (i.e., some species may have better low frequency hearing than others, like blue and fin whales; Clark and Ellison 2004), but decided there was not enough data to support such a division at this time. NMFS also considered separating sperm whales from other MF cetaceans, but there are not enough data are available to stipulate exactly how this should be done. Sperm whale placement within MF cetaceans is considered appropriate based on Ketten (2000), which classified sperm whales as having Type I cochlea, similar to other MF cetaceans.

[16] In March 2016, NMFS also proposed moving the white-beaked dolphin (*L. albirostris*) to the HF cetacean hearing group. However, upon re-evaluation, it was decided this move was not fully supported (i.e., move not supported to the level of that of the other two species in this family).

Table 1: Marine mammal hearing groups.

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 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*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

***** Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

NMFS' modification results in marine mammal hearing groups being defined in this Technical Guidance as depicted in Table 1. Table 1 defines a generalized hearing range each hearing group. This generalized hearing range was determined based on the ~65 dB[17] threshold from the normalized composite audiograms (Figure 4). For LF cetaceans and PW pinnipeds, the ~65 dB threshold resulted in a lower bound that was considered too low to be biologically plausible for these two groups. Instead, for LF cetaceans the lower frequency limit from Southall et al. 2007 was used, while for PW pinnipeds 50 Hz was chosen as a reasonable approximation for the lower frequency limit (relative to otariid pinnipeds)[18].

2.1.1 Application of Marine Mammal Hearing Groups

The application of marine mammal hearing groups occurs throughout the Technical Guidance in two ways. First, acoustic thresholds are divided by hearing group to acknowledge that not all marine mammal species have identical hearing or susceptibility to noise-induced hearing loss (NIHL). Outside the generalized hearing range, the risk of auditory impacts from sounds is considered highly unlikely or very low[19] (the exception

[17] In humans, functional hearing range is typically defined as 60 dB above the hearing threshold at greatest hearing sensitivity. To account for uncertainty associated with marine mammal hearing, NMFS based the Technical Guidance's generalized hearing range on 65 dB.

[18] Understanding of low-frequency pinniped hearing is limited (i.e., few studies have direct measurements of hearing below 100 Hz).

[19] Animals are able to detect sounds beyond their generalized hearing range by non-auditory mechanisms. However, typically, these sounds have to be extremely loud and would be considered uncomfortable (Wartzok

would be if a sound above/below this range has the potential to cause physical injury, i.e., lung or gastrointestinal tract injury from underwater explosives).

Second, marine mammal hearing groups are used in the establishment of marine mammal auditory weighting functions discussed next.

2.2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS

The ability to hear sounds varies across a species' 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 F1). Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviorally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted. For example, A-weighting for humans deemphasize frequencies below 1 kHz and above 6 kHz 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 for humans (e.g., B, C, D) 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 thresholds expressed in the SEL_{cum} [20] metric, which take into account what is known about marine mammal hearing (Southall et al. 2007; Erbe et al. 2016). The Finneran Technical Report (Finneran 2016), recently developed updated marine mammal auditory weighting functions that reflect new data on:

- Marine mammal hearing (e.g., Sills et al. 2014; Sills et al. 2015; Cranford and Krysl, 2015; Kastelein et al. 2015c)
- 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. 2014a; Kastelein et al. 2014b; Popov et al.

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and Ketten 1999). If a sound is on the edge of a hearing group's generalized hearing range and there is the potential for exposure to high sound pressure levels, then one should consider the potential for detection beyond normal auditory pathways.

[20] Auditory weighting functions are not to be applied to PTS or TTS onset acoustic thresholds expressed as the PK metric (i.e., PK thresholds are flat or unweighted within the generalized hearing range). For more information, please see Section 2.3.2.2.

2014; Finneran et al. 2015; Kastelein et al., 2015a; Kastelein et al. 2015b; Popov et al. 2015).

This recent update reflects a transition from auditory weighting functions that have previously been more similar to human dB(C) functions (i.e., M-weighting from Southall et al. 2007) to that more similar to human dB(A) functions. Updated marine mammal auditory weighting functions also provide a more consistent approach/methodology for all hearing groups.

Upon evaluation, NMFS determined that the proposed methodology in Finneran 2016 reflects the scientific literature and incorporated it directly into this Technical Guidance (Appendix A) following an independent peer review (see Appendix C 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, human auditory weighting functions provide 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 the Technical Guidance, they are meant to reflect the susceptibility of the ear to noise-induced threshold shifts (TSs). Regions of enhanced susceptibility to noise 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 the Technical Guidance, auditory weighting functions are meant to assess risk of NIHL and do not necessarily encompass the entire range of best hearing for every species within the 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 2016[21]). Separate functions were derived for each marine mammal hearing group (Figures 1 and 2).

[21] Wright 2015 provides a critique of this methodology. For NMFS' response associated with this critique, see the Federal Register notice associated with the finalized Technical Guidance, specifically the section responding to public comments.

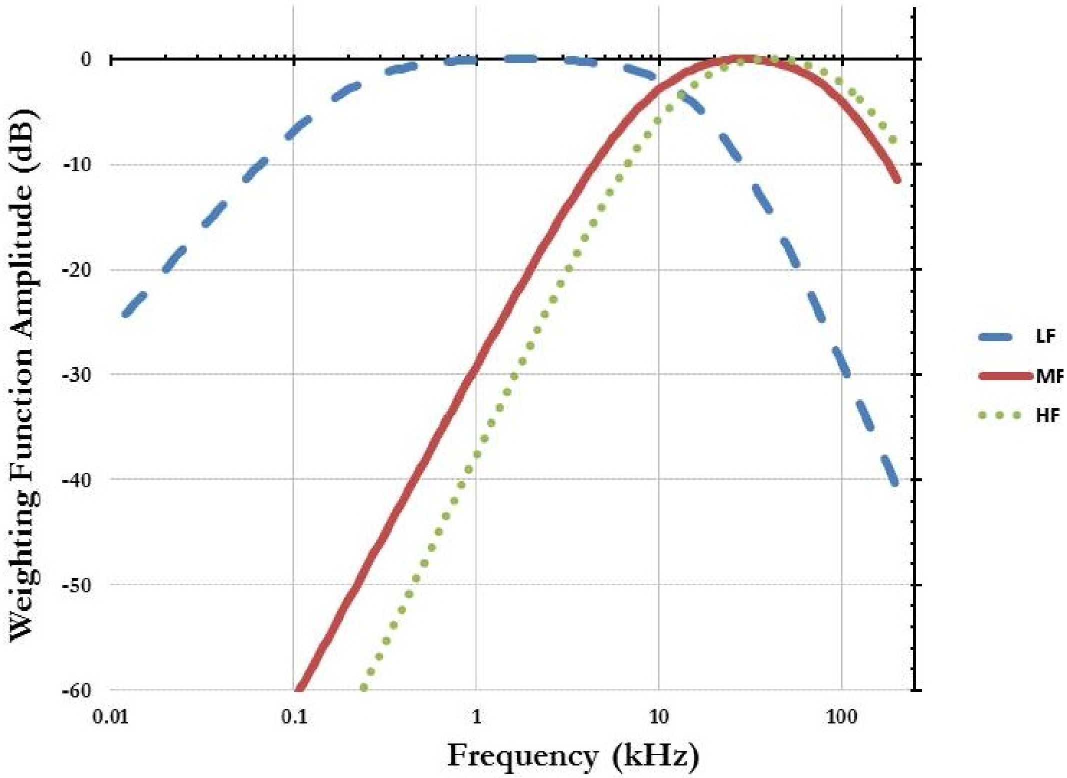

Figure 1: **Auditory weighting functions for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans.**

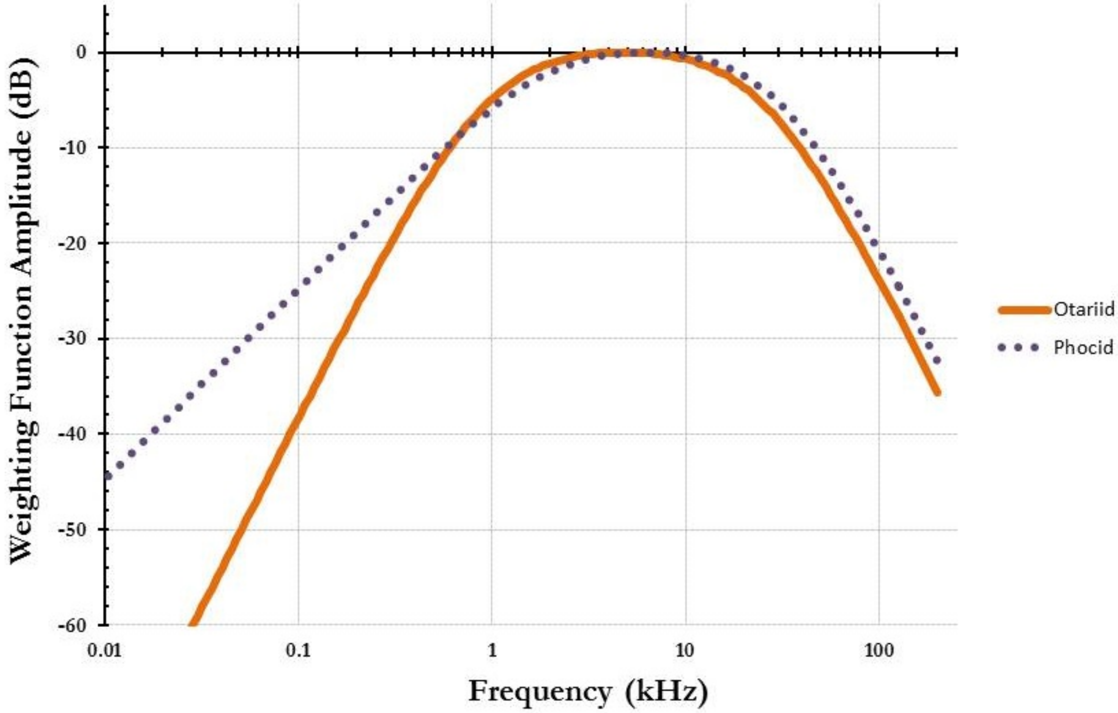

Figure 2: **Underwater auditory weighting functions for otariid (OW) and phocid (PW) pinnipeds.**

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

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

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.

- 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 (2016) illustrates the influence of each parameter value on the shape of the weighting function (Appendix A, Figure A2).

In association with auditory weighting functions are exposure functions that illustrate how auditory weighting functions relate to auditory acoustic thresholds. Exposure functions (Equation 2) are the inversion of Equation 1:

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

Equation 2

where $E(f)$ is the acoustic exposure as a function of frequency (f) and the gain parameter constant (K), which is adjusted to set the minimum value of the curve to the weighted PTS/TTS onset auditory threshold. All other parameters are 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.

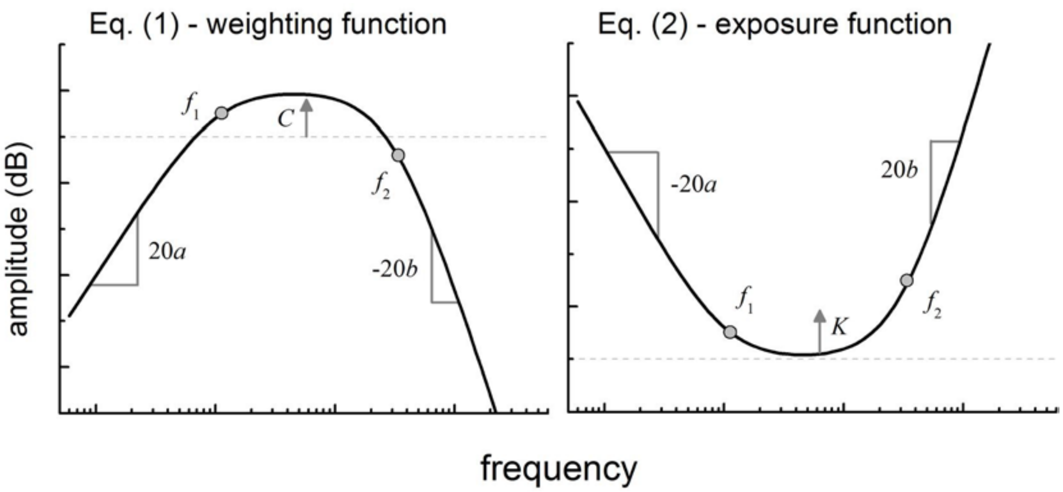

Figure 3: **Illustration of function parameter in both auditory weighting functions and exposure functions (from Finneran 2016). Reference to Equations 1 and 2 match those in the Technical Guidance.**

Finneran (2016) (Appendix A, Figures A-22 and A-23) provides a comparison of these updated auditory weighting functions with previously derived weighting functions (Finneran and Jenkins 2012 used in Navy Phase 2 Analysis).

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 (2016):

1. Derivation of marine mammal composite audiograms (original and normalized) for each hearing group (Resulting normalized composite audiogram: Figure 4; Data sources: Table 2).

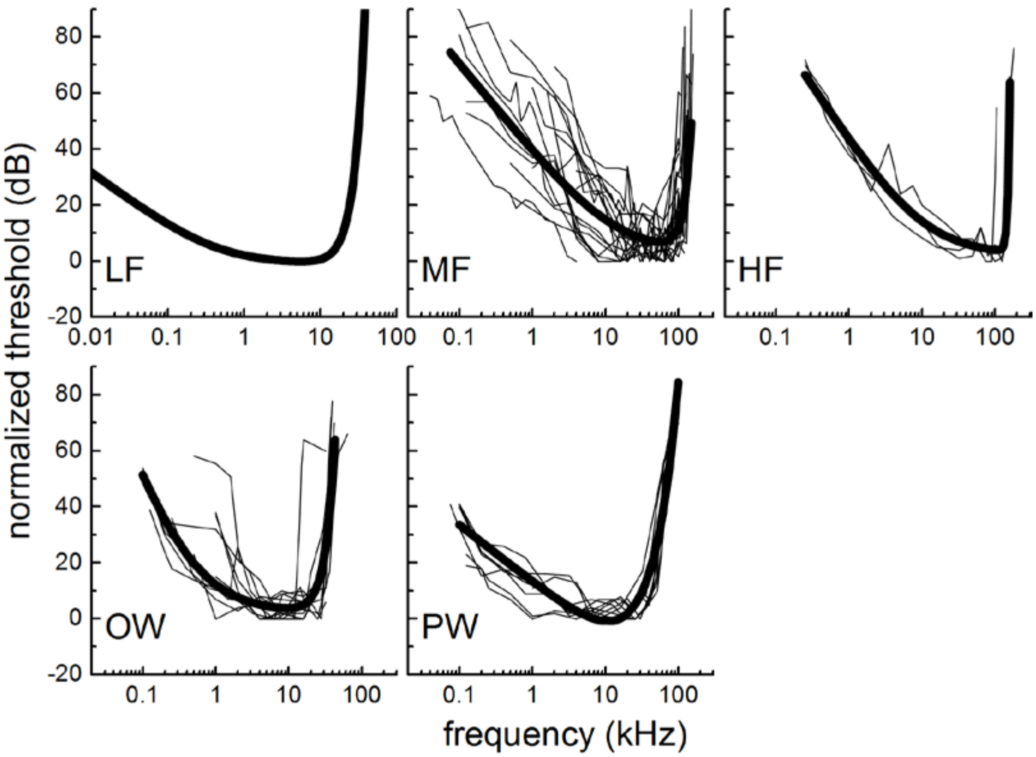

Figure 4: **Resulting normalized composite audiograms for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans and phocid (PW) and otariid (OW) pinnipeds (from Finneran 2016). For resulting original composite audiogram, see Appendix A, Figure A5.**

Table 2: Summary of data available for deriving composite audiograms.[†]

Hearing Group	Species (number of individuals)	References
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 (3)	Kastelein et al. 2010; Kastelein et al. 2015c
Phocid pinnipeds (underwater)	Harbor seal (4)	Terhune 1988; Kastelein et al. 2009b; Reichmuth et al. 2013
	Northern elephant seal (1)	Kastak and Schusterman 1999
	Ringed seal (1)	Sills et al. 2015
	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. 2005a

[†] More details on individual subjects are available in Appendix A (Table A2). Some datasets were excluded due to subjects having high-frequency hearing loss or aberrant audiograms. These included subjects from: Møhl 1968; Andersen 1970; Hall and Johnson 1972; Terhune and Ronald 1972; Terhune and Ronald 1975; Thomas et al. 1990; Wang et al. 1992; Babushina 1997; Kastak et al. 2002; Finneran et al. 2005 (Turner); Yuen et al. 2005; Finneran et al. 2007a; Sills et al. 2015 (Natchek). Decisions to exclude data were based on comparison of the individual published audiograms and ambient noise characteristics to those for other individuals of the same or closely related species. The most common reasons for excluding an individual's data were abnormal audiograms featuring high-frequency hearing loss (typically seen in older animals) or "notches" in the audiogram, or data collected in the presence of relatively high ambient noise that resulted in elevated thresholds. Excluding these data ensured that the composite audiograms were not artificially elevated, which could result in unrealistically high acoustic thresholds.

* The otariid pinniped (underwater)hearing group's composite audiogram contains data from a single Pacific walrus (*Odobenus rosmarus*) from Kastelein et al. 2002 and a single sea otter (*Enhydra lutris nereis*) from Ghoul and Reichmuth 2014, which are species under the jurisdiction of the USFWS. However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water groups to derive composite audiograms for this hearing group. 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 A4.

In deriving marine mammal composite audiograms, NMFS established an informal data hierarchy in terms of assessing these types of data. Specifically, audiograms obtained via behavioral methodologies were determined to provide the most representative (sensitive) presentation of hearing ability (Finneran et al. 2007a), followed by auditory evoked potential (AEP) data,[22] and lastly by mathematical/anatomical models for species where no data are available (i.e., LF cetaceans). Thus, the highest quality data available for a specific hearing group were used.[23]

For LF cetaceans, only two studies were available for consideration (i.e., predicted audiogram for a humpback whale from Houser et al. 2001 and fin whale from Cranford and Krysl 2015), which alone was not enough to derive a predicted audiogram for this entire hearing group. Thus, an alternative approach was used to derive a composite audiogram[24] and associated weighting function for LF cetaceans (i.e., composite audiogram parameters had to be predicted; For specifics, on this process, see Appendix A_1).

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

3. The high-frequency exponent (b) was set equal to two to match the previously derived marine mammal auditory weighting functions from Finneran and Jenkins (2012), since no new TTS measurements were 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, where the threshold

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22 Despite not directly including AEP audiograms in the development of a hearing groups' composite audiogram, these date were evaluated to ensure species were placed within the appropriate hearing group and to ensure a species where only AEP data are available were within the bounds of the composite audiogram for that hearing group. Furthermore, AEP TTS data are presented within the Technical Guidance for comparative purposes alongside TTS data collected by behavioral methods illustrating that the AEP TTS data are within the bounds (the majority of the time above) of those collected by behavioral methods.

23 Behavioral techniques for obtaining audiograms measure perception of sound by a receiver, while AEP methods measure only neural activity (Jewett and Williston 1971) (i.e., two methodologies are not necessarily equivalent). As a result, behavioral techniques consistently produce lower thresholds than those obtained by AEPs (e.g., Szymanski et al. 1999; Yuen et al. 2005; Houser and Finneran 2006). Currently, there are no means established for "correcting" AEP data so that it may be more comparable to those obtained via behavioral methods (Heffner and Heffner 2003; Finneran 2015; Sisneros et al. 2016; Erbe et al. 2016).

24 During the third public comment period on the Technical Guidance in March 2016, ambient noise levels from Clark and Ellison 2004 were offered by a group of subject matter experts as additional scientific support to NMFS' LF cetacean weighting function (for direct comparison to NOAA's 2016 LF cetacean weighting function see: https://www.regulations.gov/#!documentDetail;D=NOAA-NMFS-2013-0177-0155).

values were ΔT above the threshold at f_0 . These two parameters reflect the hearing group's most susceptible frequency range.

5. To determine ΔT, the exposure function amplitude was calculated for MF and HF cetaceans examining ΔT values ranging from zero to 20 dB. Then, the K gain parameter was adjusted to minimize the mean-squared error (MSE) between the function amplitude (original and normalized composite audiograms) and MF and HF cetacean TTS data. The value of ΔT resulting the lowest MSE was eleven for both the normalized and original data. This value was used for other hearing groups.

6. Hearing groups where TTS data are available (i.e., MF and HF cetaceans and PW and OW pinniped) were used to define K (Step 4 above). For LF cetaceans, where data were not available, TTS onset was estimated by assuming the numeric difference between auditory threshold (Figure 4, original data) and TTS onset at the frequency of best hearing (f_0) would be similar across hearing groups. For LF cetaceans auditory threshold had to be predicted, since no data exist (For specifics on methodology, see Appendix A, Table A7).

7. The weighting function parameter (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.

For each hearing group, the resulting numeric values associated with these parameters and resulting weighted TTS onset threshold for non-impulsive sources (SEL_{cum} metric) are listed in Table 3 and resulting weighting functions are depicted in Figures 1 and 2.

Table 3: Summary of weighting and exposure function parameters.

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)	Weighted TTS onset threshold* (SEL_{cum})
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179	179 dB
Mid-frequency (MF) cetaceans	1.6	2	8.8	110	1.20	177	178 dB
High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152	153 dB
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75	180	181 dB
Otariid pinnipeds (OW) (underwater)	2.0	2	0.94	25	0.64	198	199 dB

* Determined from minimum value of exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$).

Note: Appendix A, Figure A17 illustrates that the resulting exposure functions (and subsequent weighting functions) are broader than the composite audiograms or audiogram from an individual species. This is important to note because the weighting/exposure functions are derived not just from data associated with the composite audiogram but also account for available TTS onset data.

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

The application of marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of their overlap 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).

If the frequencies produced by a sound source are outside a hearing group's most susceptible hearing range (where the weighting function amplitude is 0), sounds at those frequencies must have a higher sound pressure level to produce a similar threshold shift (i.e., PTS onset) as sounds with frequencies in the hearing group's most susceptible hearing range. Because auditory weighting functions take into account a hearing group's differing susceptibility to frequencies, the implementation of these functions typically results in smaller isopleths[25] for frequencies where the group is less susceptible. Additionally, if the sound source produces frequencies completely outside the generalized hearing range of a given hearing group (i.e., has no harmonics/subharmonics that are capable of producing sound within the hearing range of a hearing group), then the likelihood of the sound causing hearing loss is considered low.[26]

Marine mammal auditory weighting functions should be used in conjunction with corresponding SEL_{cum} PTS onset acoustic thresholds. If the use of the full auditory weighting function is not possible by an action proponent (i.e., consider weighting function over multiple frequencies for broadband source), NMFS has provided an alternative tool based on a simpler weighting function (See Appendix D).

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[25] Note: Acoustic thresholds associated with a hearing group do not change depending on how much a sound may overlap a group's most susceptible frequency range. Instead, weighting functions affect exposure modeling/analysis via the resulting size of the isopleth (area) associated with the threshold based on how susceptible that particular hearing group is to the sound being modeled. For example, a hearing group could have different size isopleths associated with the same threshold, if one sound was within its most susceptible frequency range and the other was not (i.e., sound in most susceptible hearing range will result in larger isopleth compared to sound outside the most susceptible hearing range).

[26] The potential for sound to damage beyond the level the ear can perceive exists (Akay 1978), which is why the acoustic thresholds also include the PK metric, which are flat or unweighted within the generalized hearing range of a hearing group.

Tougaard et al. (2015) reviewed the impacts of using auditory weighting functions and various considerations when applying them during the data evaluation and implementation stages (e.g., consequences of using too broad or too narrow of a filter) and suggested some modifications (correction factors) to account for these considerations. However, there are no data to support doing so (i.e., selection would be arbitrary). Moreover, various conservative factors have been accounted for in the development of weighting functions and acoustic thresholds: A 6 dB threshold shift was used to represent TTS onset; the methodology does not incorporate exposures where TTS did not occur; and the potential for recovery is not accounted for. Additionally, the means by which NMFS 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 Measuring and Maintaining Full Spectrum for Future Analysis

Marine mammal auditory weighting functions should be applied after sound field measurements[27] 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, then data can still be used). Additionally, it is important to consider measurements that encompass the entire frequency band that a sound source may be capable of producing (i.e., sources often produce sounds, like harmonics/subharmonics, beyond the frequency/band of interest; e.g., Deng et al. 2014; Hastie et al. 2014).

2.3 PTS Onset Acoustic Thresholds

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.

PTS onset acoustic thresholds for marine mammals have not been directly measured and must be extrapolated from available TTS onset measurements. Thus, based on cetacean measurements from TTS studies (see Southall et al. 2007; Finneran 2015; Finneran 2016 found in Appendix A of this Technical Guidance) a threshold shift of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation[28] 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

27 Note: Sound field measurements refers to actual field measurements, which are not a requirement of this Technical Guidance, and not to exposure modeling analyses, where it may be impractical due to data storage and cataloging restraints.

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

al. 2000; Finneran et al. 2002). Thus, NMFS has set the onset of TTS at the lowest level that exceeds recorded variation (i.e., 6 dB).

There are different mechanisms (e.g., anatomical, neurophysiological) associated with TTS vs. PTS onset, making the relationship between these types of TSs 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 mammals where direct measurements of PTS exist). Thus, TTS represents the best information available from which PTS onset can be estimated.

The acoustic thresholds presented in Table 4 update all NMFS acoustic thresholds for PTS onset. The acoustic thresholds consist of both an acoustic threshold and weighting function for the SEL_{cum} metric (weighting functions are considered not appropriate for PK metric).

Table 4: Summary of PTS onset acoustic thresholds.

	PTS Onset Thresholds* (Received Level)	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{pk,flat}$: 219 dB $L_{E,LF,24h}$: 183 dB	*Cell 2* $L_{E,LF,24h}$: 199 dB
Mid-Frequency (MF) Cetaceans	*Cell 3* $L_{pk,flat}$: 230 dB $L_{E,MF,24h}$: 185 dB	*Cell 4* $L_{E,MF,24h}$: 198 dB
High-Frequency (HF) Cetaceans	*Cell 5* $L_{pk,flat}$: 202 dB $L_{E,HF,24h}$: 155 dB	*Cell 6* $L_{E,HF,24h}$: 173 dB
Phocid Pinnipeds (PW) (Underwater)	*Cell 7* $L_{pk,flat}$: 218 dB $L_{E,PW,24h}$: 185 dB	*Cell 8* $L_{E,PW,24h}$: 201 dB
Otariid Pinnipeds (OW) (Underwater)	*Cell 9* $L_{pk,flat}$: 232 dB $L_{E,OW,24h}$: 203 dB	*Cell 10* $L_{E,OW,24h}$: 219 dB

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

Note: Peak sound pressure (L_{pk}) has a reference value of 1 μPa, and cumulative sound exposure level (L_E) has a reference value of 1μPa²s. In this Table, thresholds are abbreviated to reflect American National Standards Institute standards (ANSI 2013). However, peak sound pressure is defined by ANSI as incorporating frequency weighting, which is not the intent for this Technical Guidance. Hence, the subscript "flat" is being included to indicate peak sound pressure should be flat weighted or unweighted within the generalized hearing range. The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these acoustic thresholds will be exceeded.

NMFS recognizes that the implementation of marine mammal weighting functions represents a new factor for consideration that may exceed the capabilities of some action proponents. Thus, NMFS has developed alternative tools for those who cannot fully apply weighting functions associated with the SEL_{cum} metric (See Appendix D).

2.3.1 Impulsive and Non-Impulsive Acoustic Thresholds

This Technical Guidance divides sources into impulsive and non-impulsive based on physical characteristics at the source, with impulsive sound having physical characteristics making them more injurious[29] (e.g., high peak sound 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 2016 that appears as Appendix A of this Technical Guidance).

The characteristics of the sound at a receiver, rather than at the source, are the relevant consideration 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 to effects of propagation (e.g., time dispersion/time spreading; Urick 1983; Sertlek et al. 2014).

For the purposes of this Technical Guidance,[30] sources are divided and defined as the following:

- Impulsive: produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound 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 sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998).

Note: The term "impulsive" in this document relates specifically to NIHL and specifies the physical characteristics of an impulsive sound source, which likely gives them a higher potential to cause auditory TTS/PTS. This definition captures how these sound types may be more likely to affect auditory physiology and is not meant to reflect categorizations associated with behavioral disturbance.

2.3.2 Metrics

2.3.2.1 Cumulative Sound Exposure Level (SEL_{cum}) Metric

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

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[29] 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).

[30] If there is a source where it is unclear how it should be defined, consider the most applicable definition and consult with NMFS.

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 thresholds 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 applying the SEL_{cum} metric is the equal energy hypothesis (EEH), where it is assumed that sounds of equal SEL_{cum} produce an 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 TSs (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 sound level (e.g., overall level, sensation level, or level above background), duration, duty cycle (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 TSs (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 thresholds in this Technical Guidance are also expressed as a PK 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 as those that are most likely to result in TTS in marine mammals[31] (Finneran 2015). Additionally, no currently supported alternative method to accumulate exposure is available. If alternative methods become available, they can be evaluated and considered when the Technical Guidance is updated.

Recommended Accumulation Period

To apply the SEL_{cum} 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

[31] When possible, it is valuable for action proponents to indicate the exposure conditions under which these acoustic thresholds are likely to be exceeded.

contributing to a receiver's accumulated level (Gedamke et al. 2011). Additionally, several important factors determine the likelihood and duration 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). NMFS 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[32]).

After sound exposure ceases or between successive sound exposures, the potential for recovery from hearing loss exists, with PTS resulting in incomplete recovery and TTS resulting in complete recovery. Predicting recovery from sound exposure can be quite complicated. Currently, recovery in wild marine mammals cannot be accurately quantified. However, Finneran et al. (2010a) and Finneran and Schlundt (2013) proposed a model that approximates recovery in bottlenose dolphins and whose applicability to other species and other exposure conditions has yet to be determined. In the development of the Technical Guidance's acoustic thresholds, NMFS assumes for intermittent, repeated exposure that there is no recovery between subsequent exposures, although it has been demonstrated in terrestrial mammals (Clark et al. 1987; Ward 1991) and more recently in a marine mammal studies (Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b), that there is a reduction in damage and hearing loss with intermittent exposures.

Existing NMFS acoustic thresholds have only accounted for proximity of the sound source to the receiver, but acoustic thresholds in this Technical Guidance (i.e., expressed as SEL_{cum}) now take into account the duration, as well as level of exposure. NMFS recognizes that accounting for duration of exposure, although supported by the scientific literature, 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.

NMFS 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, NMFS acknowledges that different action proponents may have different capabilities and levels of modeling sophistication. NMFS has provided a simple means of approximating exposure for applicants that are unable to apply various factors into their model (See Appendix D).

[32] For example, where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and/or exposed to a long-duration activity with a large sound source, or where a continuous stationery activity is nearby an area where marine mammals congregate, like a pinniped pupping beach.

2.3.2.2 Peak Sound Pressure Level (PK) Metric[33]

Sound exposure containing transient components (e.g., short duration and high amplitude; impulsive sounds) can create a greater risk of causing direct mechanical fatigue to the inner ear (as opposed to strictly metabolic) 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. This is the concept of "critical level," where damage switches from being primarily metabolic to more mechanical and 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 provide separate acoustic thresholds for impulsive sound sources using the PK 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 all the effects of impulsive sounds (i.e., often violates EEH; NIOSH 1998), which is why instantaneous PK level has also been chosen as part of NMFS' dual metric acoustic thresholds for impulsive sounds.[34] Auditory weighting is not considered appropriate with the PK metric, as direct mechanical damage associated with sounds having high peak sound 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). Thus, this Technical Guidance is recommends that the PK thresholds be considered unweighted/flat-weighted within the entire frequency band of a hearing group.

2.3.2.3 Comparison Among Metrics

NMFS' existing acoustic thresholds were expressed as root-mean-square sound pressure level (RMS SPL), which is a different metric from the PK and SEL_{cum} that are being recommended for the PTS onset acoustic thresholds in this Technical Guidance. Thus, NMFS recommends caution when comparing prior acoustic thresholds to those presented in this document (i.e., metrics are not directly comparable). For example, a RMS SPL threshold of 180 dB is not equal to a PK threshold of 180 dB. Further, the SEL_{cum} metric incorporates exposure duration and is an energy level with a different reference value (re: $1\mu Pa^2$-s). Thus, it is not directly comparable to other metrics that describe sound pressure levels (re: 1 μPa)[35].

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[33] Note: Peak sound pressure level should not be confused with *maximum* root mean square sound pressure level.

[34] For non-impulsive sounds, the SEL_{cum} threshold will likely to result in the largest isopleth, compared to the PK threshold. Thus, for the majority of non-impulsive sounds, the consideration of the PK threshold is unnecessary. However, if a non-impulsive sound has the potential of exceeding the PK threshold associated with impulsive sounds, these thresholds should be considered (i.e., dual metrics).

Recently, publications on how to estimate PK from SEL for seismic airguns and offshore impact pile drivers may be useful to applicants (Galindo-Romero et al. 2015; Lippert et al. 2015).

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

2.3.3 Development of PTS Onset Acoustic Thresholds

The development of the PTS onset acoustic thresholds consisted of the following procedure described in Finneran 2016 (Appendix A[36]):

1. Identification of available data on marine mammal hearing and noise-induced hearing loss (e.g., Southall et al. 2007; Finneran 2015; Finneran 2016 references 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 (32 studies found in Table 5) 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 acoustic thresholds were evaluated and summarized to extrapolate to PTS onset acoustic thresholds.

    - Studies divided into the following categories:
        - Temporal Characteristics: Impulsive and Non-impulsive

        - Marine Mammal Hearing Groups: LF Cetaceans, MF Cetaceans, HF Cetaceans, PW Pinnipeds, and OW Pinniped

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[36] Wright 2015 provides a critique of this methodology. For NMFS' response to this critique, see the Federal Register notice associated with the finalized Technical Guidance, specifically the section responding to public comments.

Table 5: Available underwater marine mammal threshold shift 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)
Kastelein et al. 2015b	6-7 kHz sweeps (non-impulsive)	Harbor porpoise (1)
Finneran et al. 2015*	Single airgun producing shots (impulsive)*	Bottlenose dolphin (3)
Popov et al. 2015	Half-octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2016*	Impact pile driving (impulsive)	Harbor porpoise (2)

+Peer reviewed studies available and evaluated as of 31 May 2016.
^Note: Some individuals have been used in multiple studies.
*No incidents of temporary threshold shift were recorded in study.

4. Determination of TTS onset threshold by individual (RLs, in both PK and SEL_{cum} metrics) based on methodology from Finneran 2016 for impulsive and non-impulsive sounds (Full detail in Appendix A).

   - Non-impulsive sounds:
     - Only TTS data from behavioral studies were used, since studies using AEP methodology typically result in larger thresholds shifts (e.g., up to 10 dB difference, Finneran et al. 2007a) and are considered to be non-representative (as illustrated in Appendix A, Figure A9)

     - 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 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 a threshold shift (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 by hearing group (Appendix A, Figures A10-A13). Note: Appendix A, Figures A18-A20 illustrate available marine mammal TTS data in relation to the composite audiogram and exposure function.

     - Finally, weighted thresholds for TTS onset were determined by the minimum value of the exposure function (Equation 2), which is mathematically equivalent to $K + C$ (Table 6).

Table 6: TTS onset auditory acoustic thresholds for non-impulsive sounds.

Hearing Group	K (dB)	C (dB)	Weighted TTS onset acoustic threshold (SEL_{cum})
Low-frequency (LF) cetaceans	179	0.13	179 dB
Mid-frequency (MF) cetaceans	177	1.20	178 dB
High-frequency (HF) cetaceans	152	1.36	153 dB
Phocid pinnipeds (underwater)	180	0.75	181 dB
Otariid pinnipeds (underwater)	198	0.64	199 dB

- Impulsive sounds:
    - Available TTS data for impulsive sources were weighted based on weighting functions for the appropriate hearing group (MF and HF cetaceans only from two studies: Finneran et al. 2002; Lucke et al. 2009).

    - For hearing groups, where impulsive TTS onset data did not exist (LF cetaceans and PW and OW pinnipeds), Finneran (2015) derived impulsive TTS onset acoustic thresholds using the relationship between non-impulsive TTS onset thresholds and impulsive TTS onset thresholds for MF and HF cetaceans (i.e., similar to what was presented in Southall et al. 2007). Using the mean/median of these data resulted in an 11 dB relationship, which was used as a surrogate for the other hearing groups (i.e., non-impulsive TTS threshold was 11 dB higher than impulsive TTS threshold).

    - A similar approach was investigated for the PK threshold, resulting in a 45 dB relationship, which was considered unrealistic (approaching cavitation level of water; Southall et al. 2007). Upon further consideration, the auditory system's dynamic range was determined a more appropriate methodology for estimating PK sound pressure acoustic thresholds.[37]

      The dynamic range methodology assumes that the PK TTS onset acoustic threshold for MF and HF cetaceans defines the upper end of those hearing groups' dynamic range (i.e., PK threshold: 224 dB for MF cetaceans and PK threshold: 196 dB for HF cetaceans), with the threshold of audibility derived from the frequency of best hearing (f_0) from the composite audiogram (i.e., 54 dB for MF cetaceans and 48 dB for HF cetaceans) defining the lower end of the groups' dynamic range.

      This results in a dynamic range of 170 dB for MF cetaceans and 148 dB for HF cetaceans. The median/mean dynamic range from these two hearing groups (i.e., 159 dB) is used as the surrogate dynamic range for LF cetaceans (best hearing at f_0= 54 dB; Resulting in a PK TTS threshold of 213 dB); PW pinnipeds (best hearing at f_0=53 dB; Resulting in a PK TTS threshold of 212 dB); and OW pinnipeds (best hearing at f_0=67 dB; Resulting in a PK TTS threshold of 226 dB).

[37] Dynamic range is used in human noise standards to define the PK acoustic threshold for impulsive sounds (e.g., 140 dB from OSHA 29 CFR 1910.95). For the purposes of this Technical Guidance, the intent is to relate the threshold of audibility and TTS onset level, not the threshold of pain, as dynamic range is typically defined (Yost 2007).

5. Extrapolation for PTS onset threshold (in both PK and SEL metrics) based on data from humans and terrestrial mammals, with the assumption that the mechanisms associated with noise-induced TS in marine mammals is similar, if not identical, to that recorded in terrestrial mammals.

    - Non-impulsive sounds:
        - PTS onset acoustic thresholds were estimated using TTS growth rates based on those marine mammal studies where 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 A10-A13).

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

        - Offset between TTS and PTS onset acoustic thresholds were examined and ranged from 13 to 37 dB (mean/median: 25/25 dB for cetacean data). Thus, based on these data, a conservative 20 dB offset was chosen to estimate PTS onset thresholds from TTS onset thresholds for non-impulsive sources (i.e., 20 dB was added to K to determine PTS onset, assuming the shape of the PTS exposure function is identical to the TTS exposure function for that hearing group).

    - Impulsive sounds: Based on limited available marine mammal impulsive data, the relationships previously derived in Southall et al. (2007), which relied upon 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 thresholds in the SEL_{cum} metric.

        - Southall et al. (2007) recommended a 6 dB of TTS/dB of noise growth rate for PK acoustic thresholds. This recommendation was based on several factors, including ensuring that the PK acoustic threshold did not unrealistically exceed the cavitation threshold of water. Resulting in an approximate 6 dB difference between TTS and PTS onset thresholds in the PK metric.

III. UPDATING OF ACOUSTIC TECHNICAL GUIDANCE AND ACOUSTIC THRESHOLDS

Research on the effects of anthropogenic sound on marine mammals has increased dramatically in the last decade and will likely continue to increase in the future. As such, the Technical Guidance will be reviewed periodically and updated as appropriate to reflect the compilation, interpretation, and synthesis of the scientific literature.

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

3.1 PROCEDURE AND TIMELINE FOR UPDATING THE TECHNICAL GUIDANCE

NMFS will continue to monitor and evaluate new data as they become available and periodically convene staff from our various offices, regions, and science centers to update the Technical Guidance as appropriate (anticipating updates to occur on a three to five year cycle). In addition to evaluating new, relevant scientific studies, NMFS will also periodically re-examine basic concepts and definitions (e.g., 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

Since the methodology for deriving composite audiograms and associated marine mammal auditory weighting functions, as well as TTS thresholds is data driven, any new information that becomes available has the potential to cause some amount of change for that specific hearing group but also other hearing groups, if they rely on surrogate data. It may not be feasible to make changes every time a new data point becomes available. Instead, NMFS will periodically examine new data to date and consider the impacts of those studies on the Technical Guidance to determine what revisions/updates may be appropriate. At the same time, there may be special circumstances that merit evaluation of data on a more accelerated timeline (e.g., LF cetacean data that could result in significant changes to the current Technical Guidance).

APPENDIX A: FINNERAN TECHNICAL REPORT

The entire Finneran Technical Report (Finneran 2016), regarding methodology for deriving auditory weighting functions and acoustic thresholds for marine mammal species under NMFS' jurisdiction, is included for reference in Appendix A. Its contents have not been modified by NMFS, other than adding "A" before figures and tables to denote Appendix A and be consistent with the other appendices in the Technical Guidance.

<u>Note</u>: 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 Technical Guidance). Additionally, terminology, symbols, and abbreviations used in this appendix may not match those used elsewhere in the Technical Guidance.

Since the final Finneran Technical Report was received an additional TTS study became available (Kastelein et al. 2016). Information regarding this study is added as a footnote by NMFS.

TECHNICAL REPORT XXXX
May 2016

Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise

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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 on marine mammals 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.

Marine mammals were divided into six 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), sirenians (group SI: manatees), phocids in water (group PW: true seals), and 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 of and effects of noise on marine mammals. The resulting weighting function amplitudes are illustrated in Figure AE-1; Table AE-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.

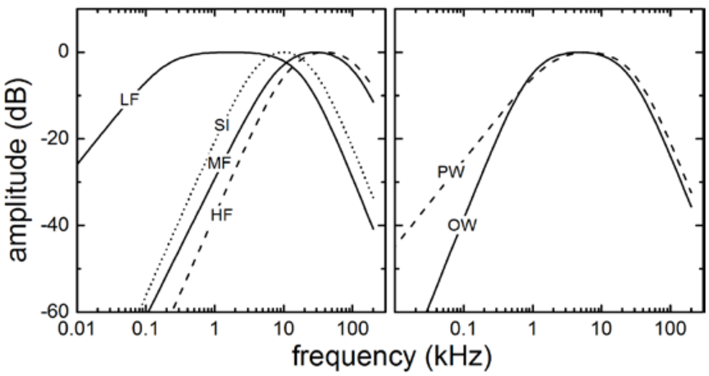

Figure AE-1. Navy Phase 3 weighting functions for all species groups. Parameters required to generate the functions are provided in Table AE-1.

Table AE-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	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

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 AE-2 and AE-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.

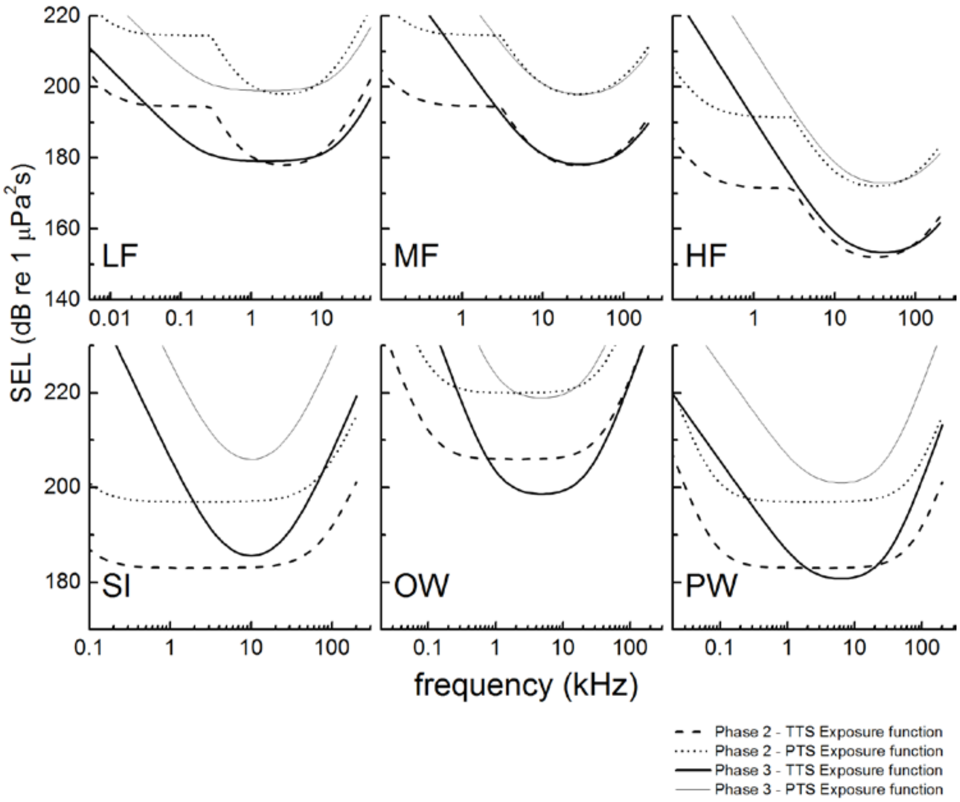

Figure AE-2. TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table AE-1). Thin solid lines — Navy Phase 3 PTS exposure functions (Table AE-1). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

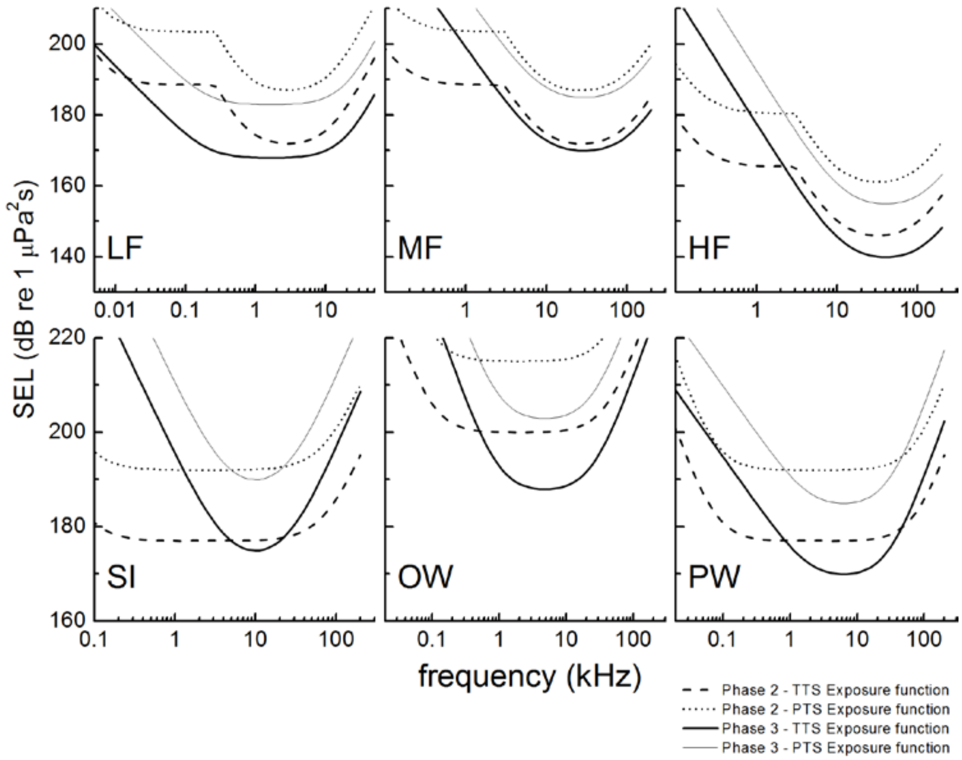

Figure AE-3. TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table AE-1). Thin solid lines — Navy Phase 3 PTS exposure functions (Table AE-1). Dashed lines — Navy Phase 2 TTS exposure functions. 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 generally 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 to human auditory weighting functions. (2) Impulsive TTS/PTS thresholds near the region of best hearing sensitivity are lower for Phase 3 compared to Phase 2.

I. 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 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 marine mammals exposed to underwater sound from 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 underwater sound during naval activities.

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 based on *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, 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., Dow Piniak et al., 2012; Martin et al., 2012; Ghoul and Reichmuth, 2014; Sills et al., 2014; Sills et al., 2015), marine mammal equal latency contours (e.g., Reichmuth, 2013; Wensveen et al., 2014; Mulsow et al., 2015), and the 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 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., 2015c; Kastelein et al., 2015b; Popov et al., 2015). 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.

Marine mammals were divided into six groups for analysis. For each group, a 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 influence the weighting function shape for 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 groups for which TTS data did not exist.

II. WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

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

$$W(f) = C + 10\log_{10}\left\{\frac{\left(f/f_1\right)^{2a}}{\left[1+\left(f/f_1\right)^2\right]^a\left[1+\left(f/f_2\right)^2\right]^b}\right\}, \qquad \text{(A1)}$$

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. A1 and A2, 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 chosen to set the maximum amplitude of W to 0 dB (i.e., the value of C does not necessarily equal the peak amplitude of the curve).

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 (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.

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 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 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.

If a = 2 and b = 2, Eq. (A1) 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 available experimental data. During implementation, the weighting function defined by Eq. (A1) is used in conjunction with a weighted threshold for TTS or PTS expressed in units of SEL.

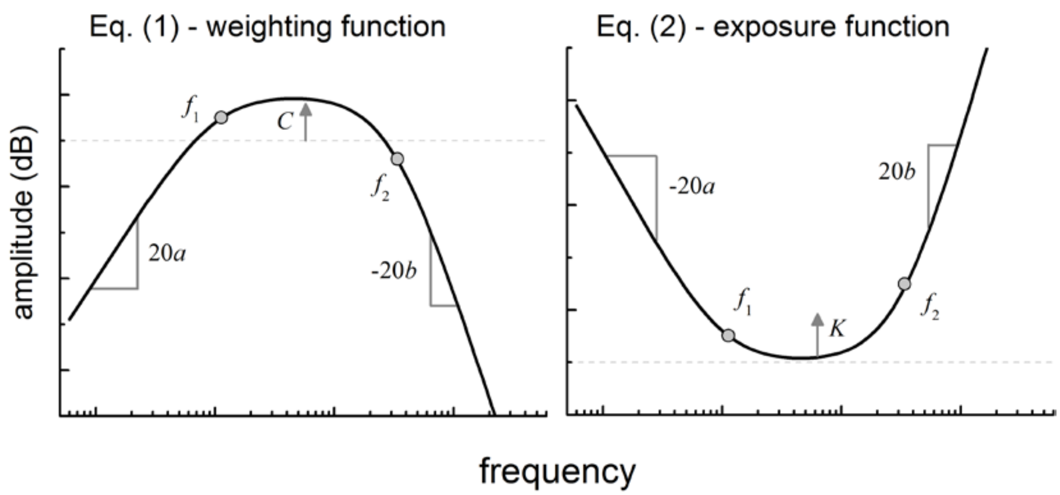

Figure A1. **Examples of (left) weighting function amplitude described by Eq. (A1) and (right) exposure function described by Eq. (A2). The parameters f_1 and f_2 specify the extent of the filter pass-band, while the exponents a and b control the rate of amplitude change below f_1 and above f_2, respectively. 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.**

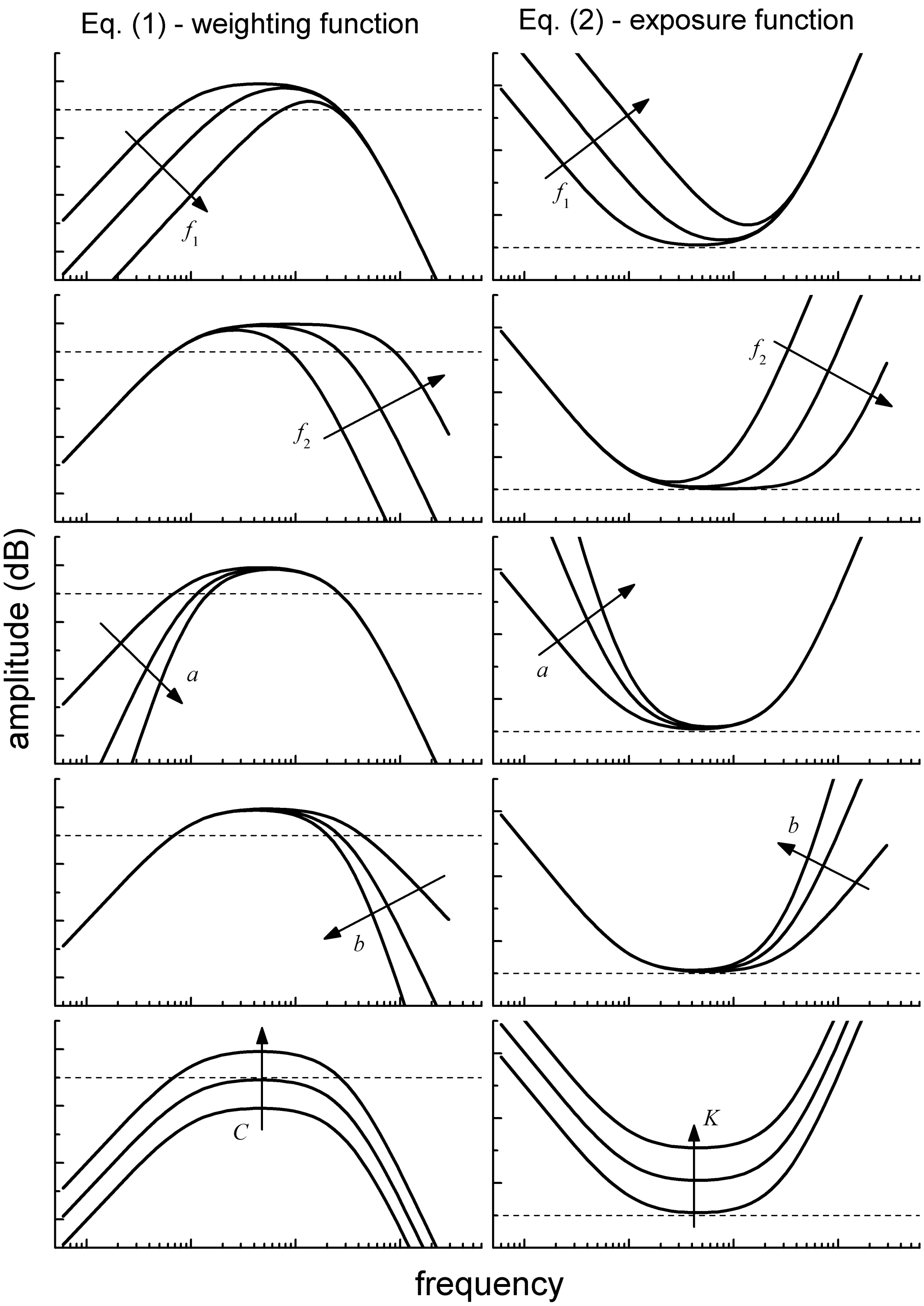

Figure A2. Influence of parameter values on the resulting shapes of the weighting functions (left) and exposure functions (right). The arrows indicate the direction of change when the designated parameter is increased.

For developing and visualizing the effects of the various weighting functions, it is helpful to invert Eq. (A1), yielding

$$E(f) = K - 10\log_{10}\left\{\frac{\left(f/f_1\right)^{2a}}{\left[1+\left(f/f_1\right)^2\right]^a\left[1+\left(f/f_2\right)^2\right]^b}\right\}, \tag{A2}$$

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. (A1), and K is a constant. The function described by Eq. (A2) has a "U-shape" similar to an audiogram or equal loudness/latency contour (Figs. A1 and A2, right panels). If K is adjusted to set the minimum value of $E(f)$ to match the weighted threshold for the onset of TTS or PTS, Eq. (A2) reveals the manner in which the exposure necessary to cause TTS or PTS varies with frequency. Equation (A2) therefore allows the frequency-weighted threshold values to be directly compared to TTS data. The function defined by Eq. (A2) 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. A3 shows the Navy Phase 2 weighting function [Eq. (A1), left panel] and TTS exposure function [Eq. (A2), right panel] for mid-frequency cetaceans exposed to sonars.

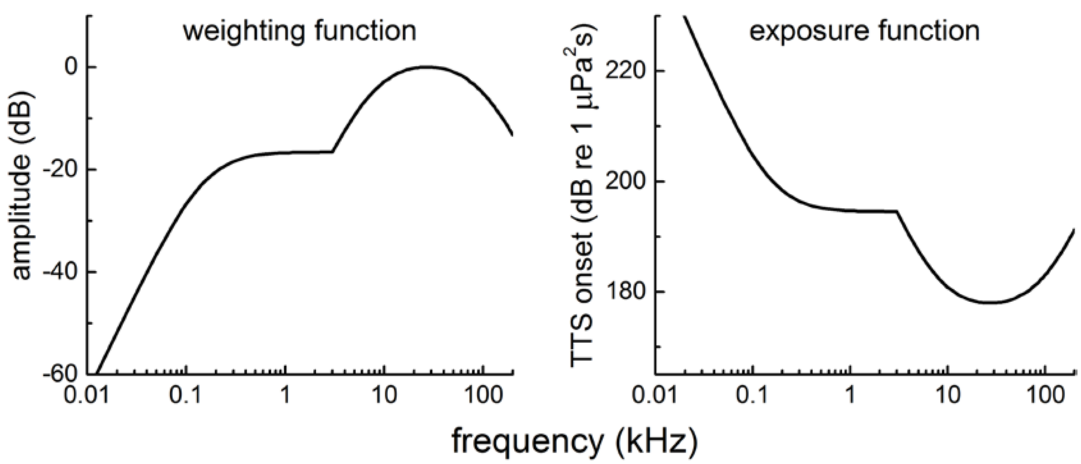

Figure A3. **(left panel) Navy Phase 2 weighting function for the mid-frequency cetacean group. This function was used in conjunction with a weighted TTS threshold of 178 dB re 1 µPa²s. For narrowband signals, the effective, weighted TTS threshold at a particular frequency is calculated by adding the weighting function amplitude at that frequency to the weighted TTS threshold (178 dB re 1 µPa²s). 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.**

The relationships between Eqs. (A1) and (A2) may be highlighted by defining the function $X(f)$ as

$$X(f) = 10\log_{10}\left\{\frac{\left(f/f_1\right)^{2a}}{\left[1+\left(f/f_1\right)^2\right]^a\left[1+\left(f/f_2\right)^2\right]^b}\right\}. \tag{A3}$$

The peak value of $X(f)$ depends on the specific values of f_1, f_2, a, and b and will not necessarily equal zero. Substituting Eq. (A3) into Eqs. (A1) and (A2) results in

$$W(f) = C + X(f) \tag{A4}$$

and

$$E(f) = K - X(f), \tag{A5}$$

respectively. The maximum of the weighting function and the minimum of the exposure function occur at the same frequency, denoted f_p. The constant C is defined so the weighting function maximum value is 0 dB; i.e., $W(f_p) = 0$, so

$$W(f_p) = 0 = C + X(f_p). \tag{A6}$$

The constant K is defined so that the minimum of the exposure function [i.e., the value of $E(f)$ when $f = f_p$] equals the weighted TTS or PTS threshold, T_{wgt}, so

$$E(f_p) = T_{wgt} = K - X(f_p). \tag{A7}$$

Adding Eqs. (A6) and (A7) results in

$$T_{wgt} = C + K. \tag{A8}$$

The constants C, K, and the weighted threshold are therefore not independent and any one of these parameters can be calculated if the other two are known.

III. 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. (A1) and (A2). 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, anatomical data, and TTS data when available.

Although the weighting function shapes are heavily influenced by the shape of the auditory sensitivity curve, the two are not identical. Essentially, the auditory sensitivity curves are adjusted to match the existing TTS data in the frequency region near best sensitivity (step 4 below). This results in "compression" of the auditory sensitivity curve in the region near best sensitivity to allow the weighting function shape to match the TTS data, which show less change with frequency compared to hearing sensitivity curves in the frequency region near best sensitivity.

Weighting and exposure function derivation consisted of the following steps:

1. Marine mammals were divided into six 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 estimated.

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. (A2) and the steady-state (non-impulsive) TTS onset data. For other species, K was defined to provide the best estimate for TTS onset at a representative frequency. The minimum value of the TTS exposure function (which is not necessarily equal to K) was then defined as the weighted TTS threshold.

6. The constant *C* was defined to set the peak amplitude of the function defined by Eq. (A1) to zero. This is mathematically equivalent to setting C equal to the difference between the weighted threshold and *K* [see Eq. (A8)].

7. 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.

8. 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. Peak SPL thresholds were estimated using the relationship between hearing thresholds and the impulse TTS peak SPL thresholds for the mid- and high-frequency cetaceans.

The remainder of this document addresses these steps in detail.

IV. MARINE MAMMAL SPECIES GROUPS

Marine mammals were divided into six groups (Table A1), 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 LF 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 there is insufficient knowledge to justify separating species into multiple groups. Therefore, a single species group is used for all mysticetes.

4.2 MID-FREQUENCY (MF) CETACEANS

The MF cetacean 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

The HF cetacean 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 SIRENIANS

The sirenian group contains manatees and dugongs. Behavioral and AEP threshold measurements for manatees have revealed lower upper cutoff frequencies and sensitivities compared to the mid-frequency cetaceans.

4.5 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.

4.6 OTARIIDS AND OTHER NON-PHOCID MARINE CARNIVORES

This group contains all eared seals (fur seals and sea lions), walruses, sea otters, and polar bears. The division of marine carnivores by placing phocids in one group and all others into a second group was made after considering auditory anatomy and measured audiograms for the various species and noting the similarities between the non-phocid audiograms (Fig. A4). Underwater hearing thresholds exist for some Northern Hemisphere species in this group.

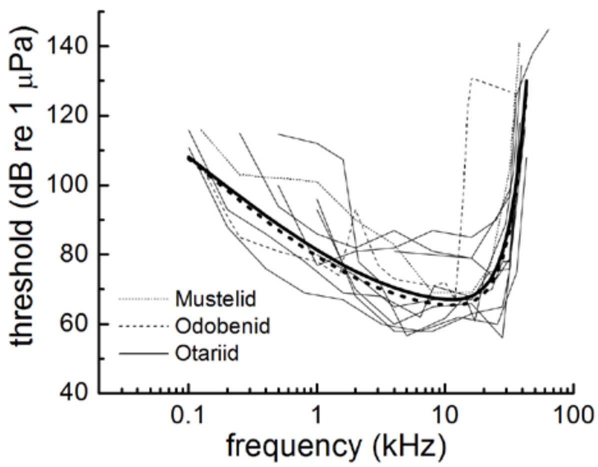

Figure A4. Comparison of Otariid, Mustelid, and Odobenid psychophysical hearing thresholds measured underwater. The thick, solid line is the composite audiogram based on data for all species. The thick, dashed line is the composite audiogram based on the otariids only.

Table A1. 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)
SI	Sirenians	Family Trichechidae (manatees) Family Dugongidae (dugongs)
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)
PW	Phocids (water)	Family Phocidae (true seals)

V. 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 species groups with three or more behavioral audiograms (all groups except LF 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, since the AEP data will systematically over-estimate thresholds and therefore over-estimate the low-frequency slope of the audiogram. As a result of this rule, behavioral data were used for all marine mammal groups.

   For the low-frequency cetaceans, for which no behavioral or AEP threshold data exist, hearing thresholds were estimated by synthesizing information from anatomical measurements, mathematical models of hearing, and animal vocalization frequencies (see Appendix A1).

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.

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.

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.

Table A2 lists the individual references for the data ultimately used to construct the composite audiograms (for all species groups except the LF cetaceans). From these data, the median (50th percentile) threshold value was calculated at each frequency and fit by the function

$$T(f) = T_0 + A\log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \qquad \text{(A9)}$$

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. (A9) 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. (A9), which allows a more shallow slope in the region of best sensitivity. Equation (A9) was fit to the median threshold data using nonlinear regression (National Instruments LabVIEW 2015). 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. Equation (A9) was also used to describe the shape of the estimated audiogram for the LF cetaceans, with the parameter values chosen to provide reasonable thresholds based on the limited available data regarding mysticete hearing (see Appendix A1 for details).

Figures A5 and A6 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. A6. To allow comparison with other audiograms based on the original threshold data, the lowest threshold for the low-frequency cetaceans was estimated to be 54 dB re 1 μPa, based on the median of the thresholds for the other in-water species groups (MF, HF, SI, OW, PW). From the composite audiograms, the frequency of lowest threshold, f_0, and the slope at the lower frequencies, s_0, were calculated (Table A5). For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one decade beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A1).

Table A2. References, species, and individual subjects used to derive the composite audiograms.

Group	Reference	Species	Subjects
MF	(Finneran et al., 2005b)	*Delphinapterus leucas*	Beethoven
	(Szymanski et al., 1999)	*Orcinus 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., 2010b)	*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., 2002a)**	*Phocoena phocoena*	PpSH047
	(Kastelein et al., 2010)	*Phocoena phocoena*	Jerry
	(Kastelein et al., 2015a)	*Phocoena phocoena*	ID No. 04
SI	(Gaspard et al., 2012)	*Trichechus manatus*	Buffet, Hugh
	(Gerstein et al., 1999)	*Trichechus manatus*	Stormy, Dundee
OW	(Moore and Schusterman, 1987)	*Callorhinus ursinus*	Lori, Tobe
	(Babushina et al., 1991)	*Callorhinus ursinus*	N/a
	(Kastelein et al., 2002b)	*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
	(Reichmuth et al., 2013)	*Phoca vitulina*	Sprouts
	(Kastelein et al., 2009)	*Phoca vitulina*	01, 02
	(Sills et al., 2014)	*Phoca largha*	Amak, Tunu
	(Sills et al., 2015)	*Pusa hispida*	Nayak

** Corrected thresholds from Kastelein et al. (2010) were used.

Table A3. Composite audiogram parameters values for use in Eq. (A9). For all groups except LF cetaceans, values represent the best-fit parameters from fitting Eq. (A9) to experimental threshold data. For the low-frequency cetaceans, parameter values for Eq. (A9) were estimated as described in Appendix A1.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	53.19	0.412	9.4	20	3.2	–
MF	46.2	25.9	47.8	35.5	3.56	0.977
HF	46.4	7.57	126	42.3	17.1	0.968
SI	-40.4	3990	3.8	37.3	1.7	0.982
OW	63.1	3.06	11.8	30.1	3.23	0.939
PW	43.7	10.2	3.97	20.1	1.41	0.907

Table A4. Normalized composite audiogram parameters values for use in Eq. (A9). For all groups except LF cetaceans, values represent the best-fit parameters after fitting Eq. (A9) to normalized threshold data. For the low-frequency cetaceans, parameter values for Eq. (A9) were estimated as described in Appendix A1.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	-0.81	0.412	9.4	20	3.2	–
MF	3.61	12.7	64.4	31.8	4.5	0.960
HF	2.48	9.68	126	40.1	17	0.969
SI	-109	5590	2.62	38.1	1.53	0.963
OW	2.36	0.366	12.8	73.5	3.4	0.958
PW	-39.6	368	2.21	20.5	1.23	0.907

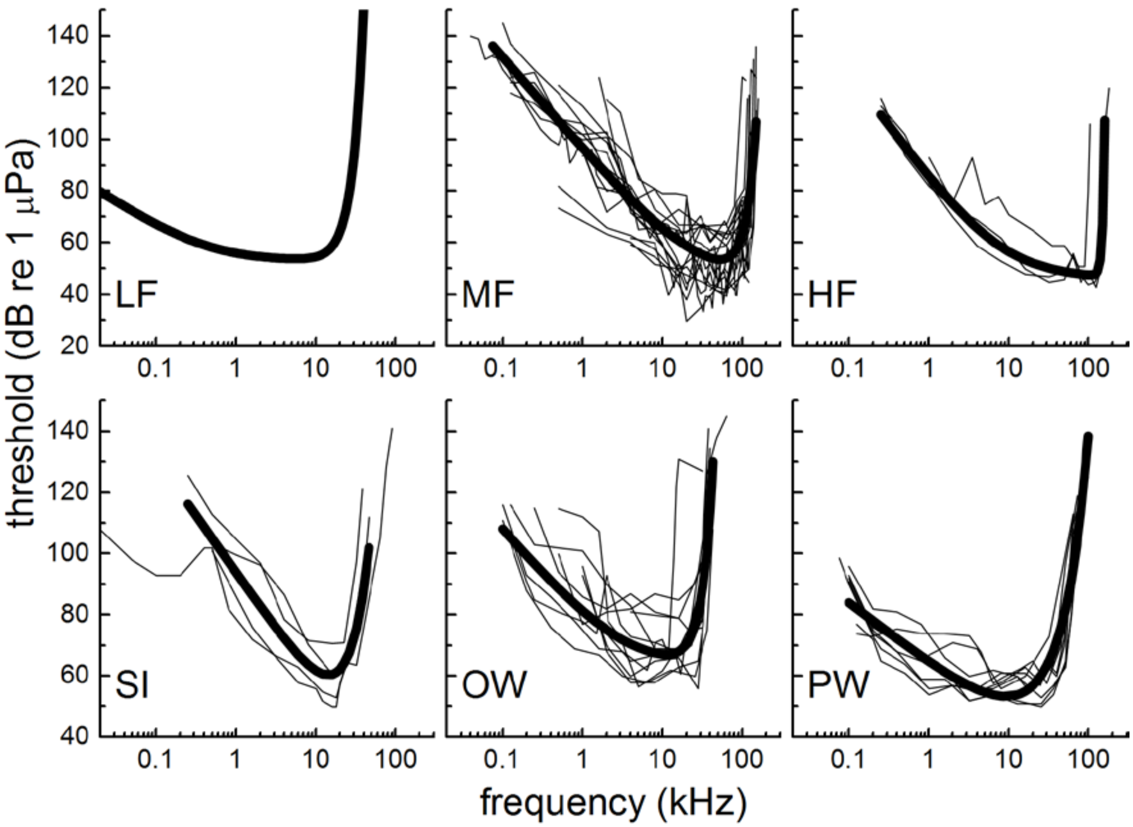

Figure A5. **Thresholds and composite audiograms for the six species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the predicted threshold curve (LF cetaceans) or the best fit of Eq. (A9) to experimental data (all other groups). Derivation of the LF cetacean curve is described in Appendix A1. The minimum threshold for the LF cetaceans was estimated to be 54 dB re 1 μPa, based on the median of the lowest thresholds for the other groups.**

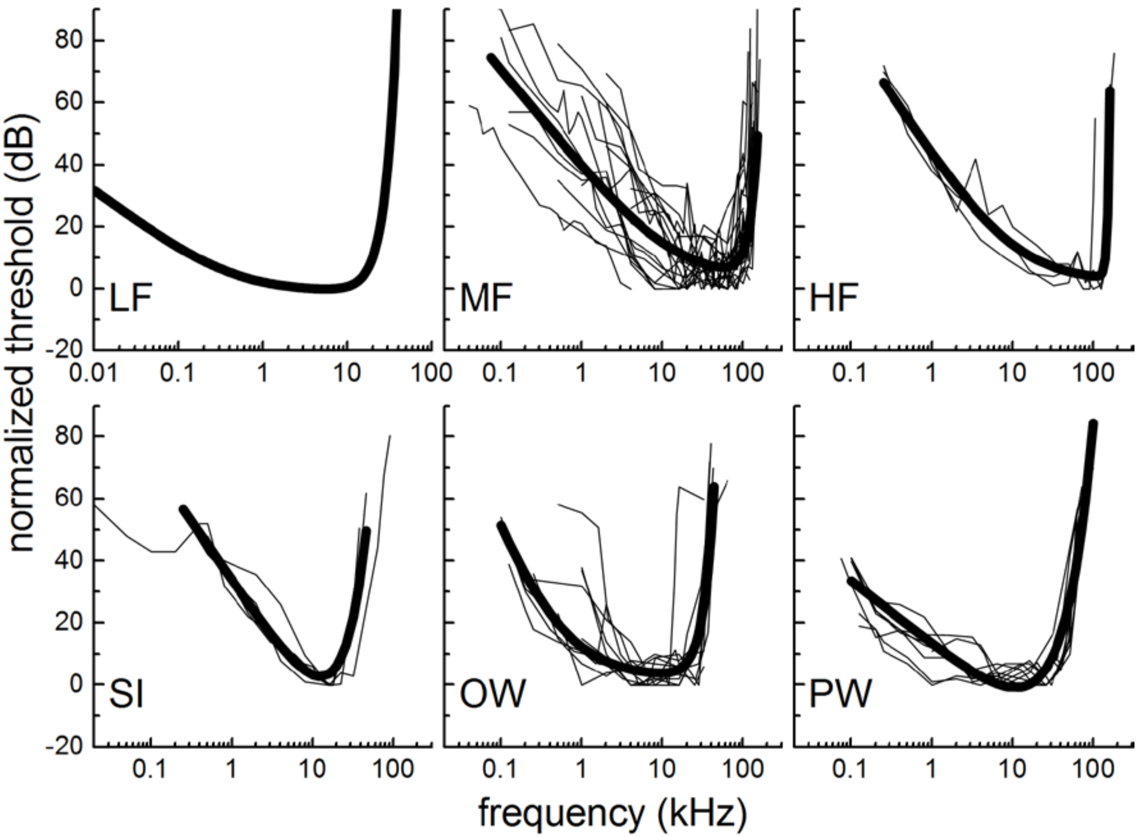

Figure A6. **Normalized thresholds and composite audiograms for the six species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the predicted threshold curve (LF cetaceans) or the best fit of Eq. (A9) to experimental data (all other groups). Thresholds were normalized by subtracting the lowest value for each individual data set (i.e., within-subject). Composite audiograms were then derived from the individually normalized thresholds (i.e., the composite audiograms were not normalized and may have a minimum value ≠ 0). Derivation of the LF cetacean curve is described in Appendix A1.**

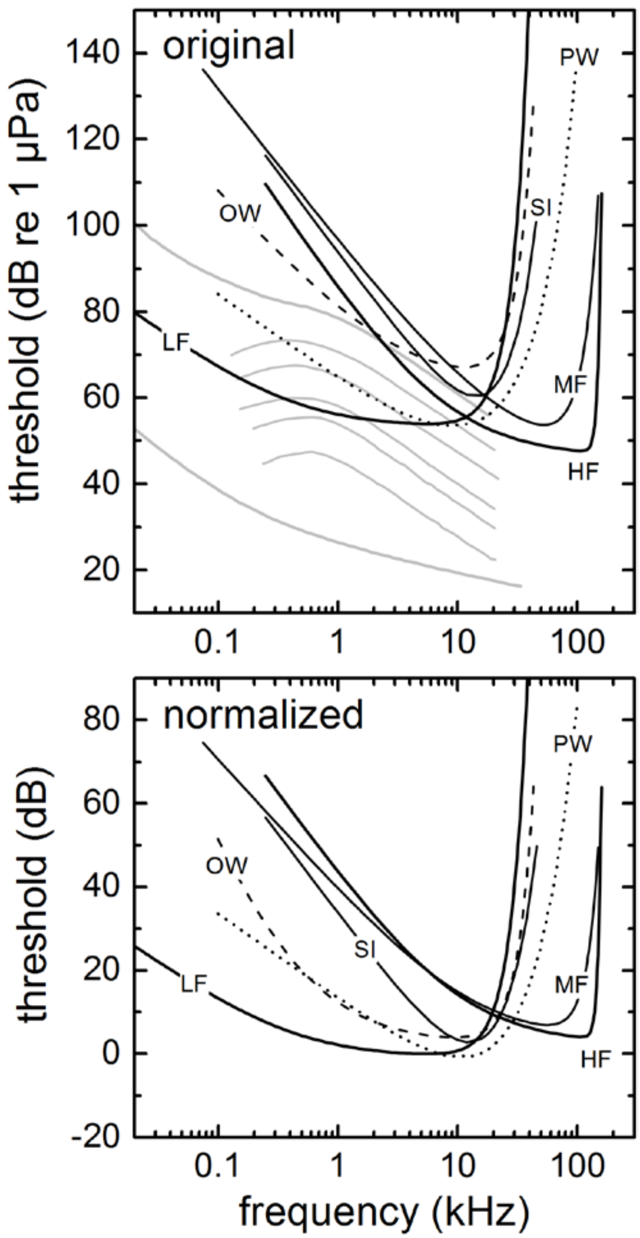

Figure A7. **Composite audiograms for the various species groups, derived with the original data (upper) and normalized data (lower). The gray lines in the upper left panel represent ambient noise spectral density levels (referenced to the left ordinate, in dB re 1 μPa^2/Hz) corresponding to the limits of prevailing noise and various sea-state conditions, from 0.5 to 6 (National Research Council (NRC), 2003).**

Table A5. **Frequency of best hearing (f_0) and the magnitude of the low-frequency slope (s_0) derived from composite audiograms and equal latency contours. For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one decade beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A1). Equal latency slopes were calculated from the available equal latency contours (Fig. A8).**

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	5.6	20	5.6	20	—
MF	55	35	58	31	31
HF	105	37	105	36	50
SI	16	36	12	37	—
OW	12	27	10	39	—
PW	8.6	19	13	20	—

VI. 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.

VII. 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. A8, 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.

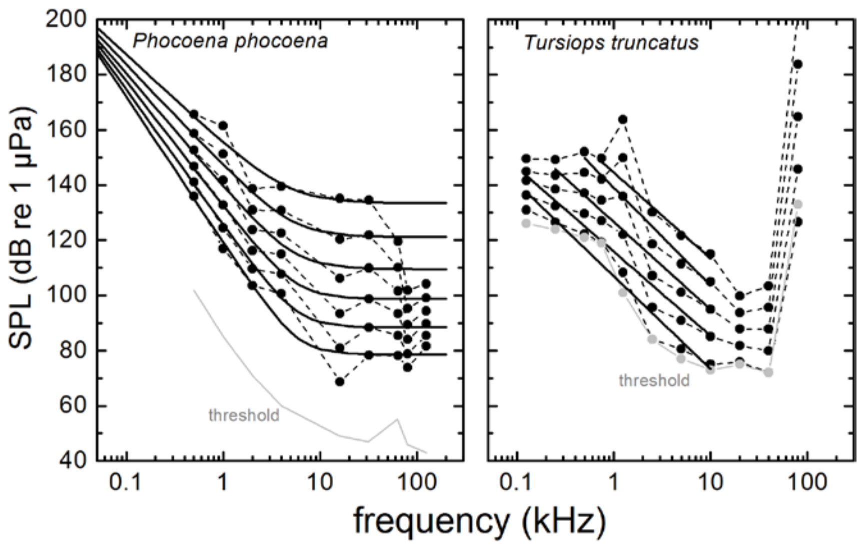

Figure A8. **Underwater marine mammal equal latency contours are available for *Phocoena phocoena* (Wensveen et al., 2014) and *Tursiops truncatus* (Mulsow et al., 2015). The slopes for the contours at low frequencies were obtained from the literature (*Phocoena phocoena*) or calculated from the best 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 A5.**

VIII. 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. A9). 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).

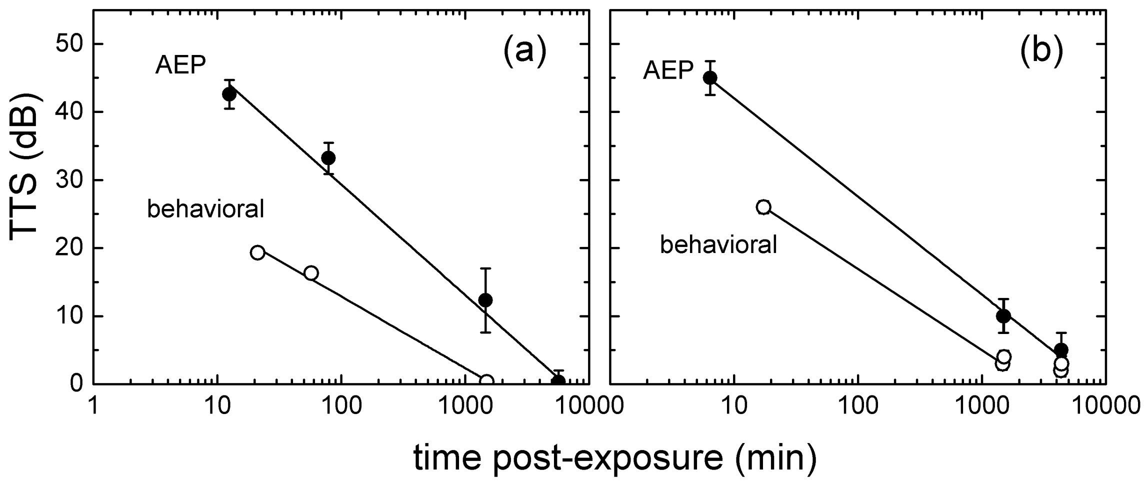

Figure A9. TTS measured using behavioral and AEP methods do not necessarily agree, with marine mammal studies reporting larger TTS obtained using AEP methods. For the data above, thresholds were determined using both techniques before and after the same noise exposure. Hearing thresholds were measured 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 μPa^2s) and (b) three 16-s tones at 20 kHz, with mean SPL = 193 dB re 1 μPa (cumulative SEL = 210 dB re 1 μPa^2s). 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., 2010b). 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 (see Finneran, 2015). 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 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

$$t(L) = m_1 \log_{10}\left[1 + 10^{(L-m_2)/10}\right], \qquad \text{(A10)}$$

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. (10) 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 A10 to A13 show all behavioral and AEP TTS data to which growth curves defined by Eq. (A10) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Table A6.

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 (e.g., Nachtigall et al., 2000; Finneran et al., 2005b). 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. This means that 40 dB of TTS, measured a few minutes after exposure, can be used as a conservative estimate for the onset of PTS. An exposure causing 40 dB of TTS is therefore considered equivalent to PTS onset.

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. A12(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. (2015c)[38] 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

[38] Footnote added by NMFS: Since the NMFS received this version of the Finneran Technical Report, another TTS study became available (Kastelein et al. 2016). In this study, two harbor porpoises were exposed to playbacks of impact pile driving strikes. Neither individual had a TTS of 6 dB after exposure. Kastelein et al. 2016 estimated TTS onset to occur at SEL_{cum} 175 dB (unweighted).

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 = 203 dB re 1 μPa). Reichmuth et al. (2016) exposed two spotted seals (*Phoca largha*) and two ringed seals (*Pusa hispida*) to single impulses from a 10 in^3 sleeve air gun with no measurable TTS (maximum unweighted SEL = 181 dB re 1 μPa^2s, peak SPL ~ 203 dB re 1 μPa).

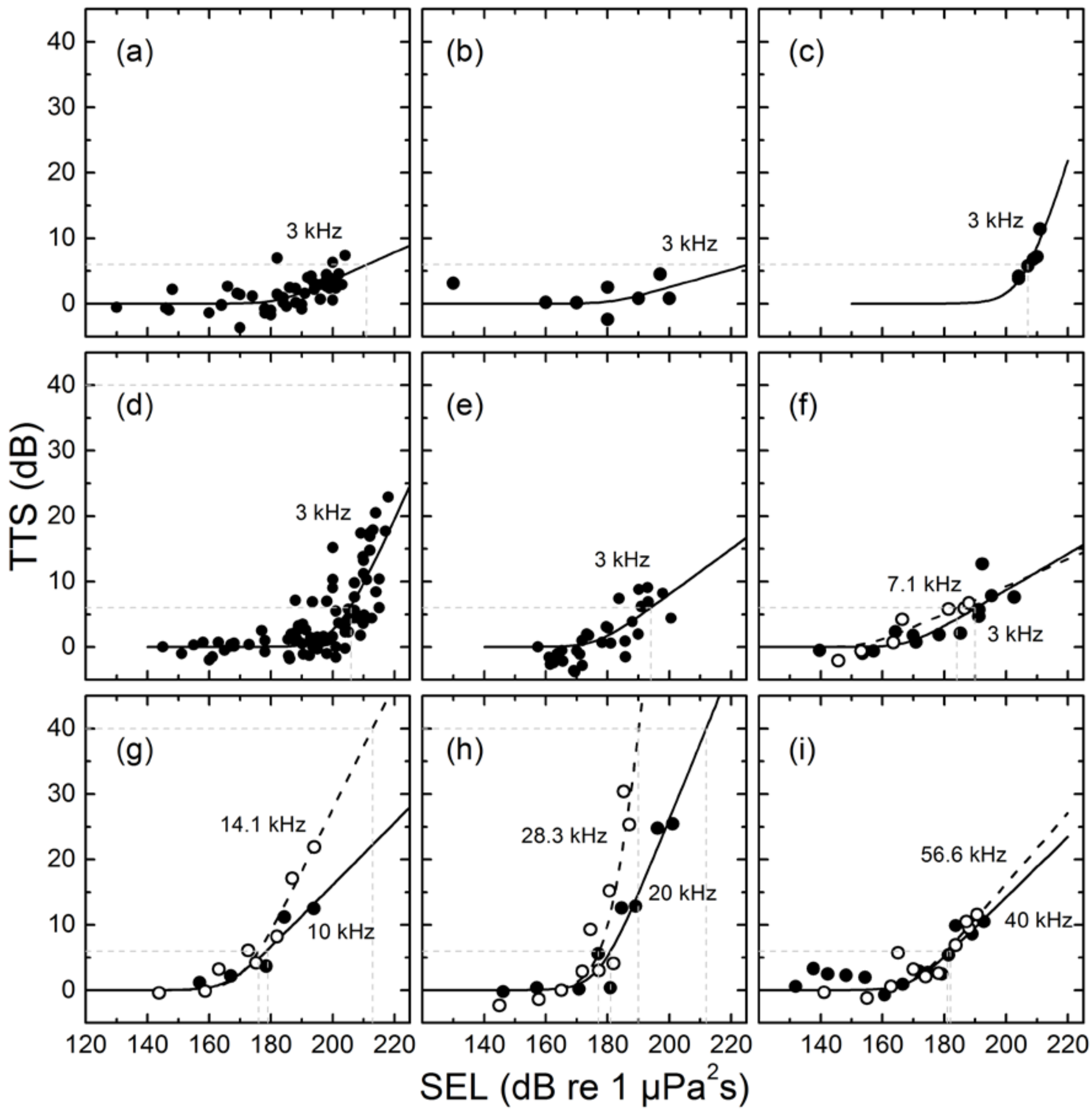

Figure A10. **TTS growth data for mid-frequency cetaceans obtained using behavioral methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel. Frequencies listed in each panel denote the exposure frequency.**

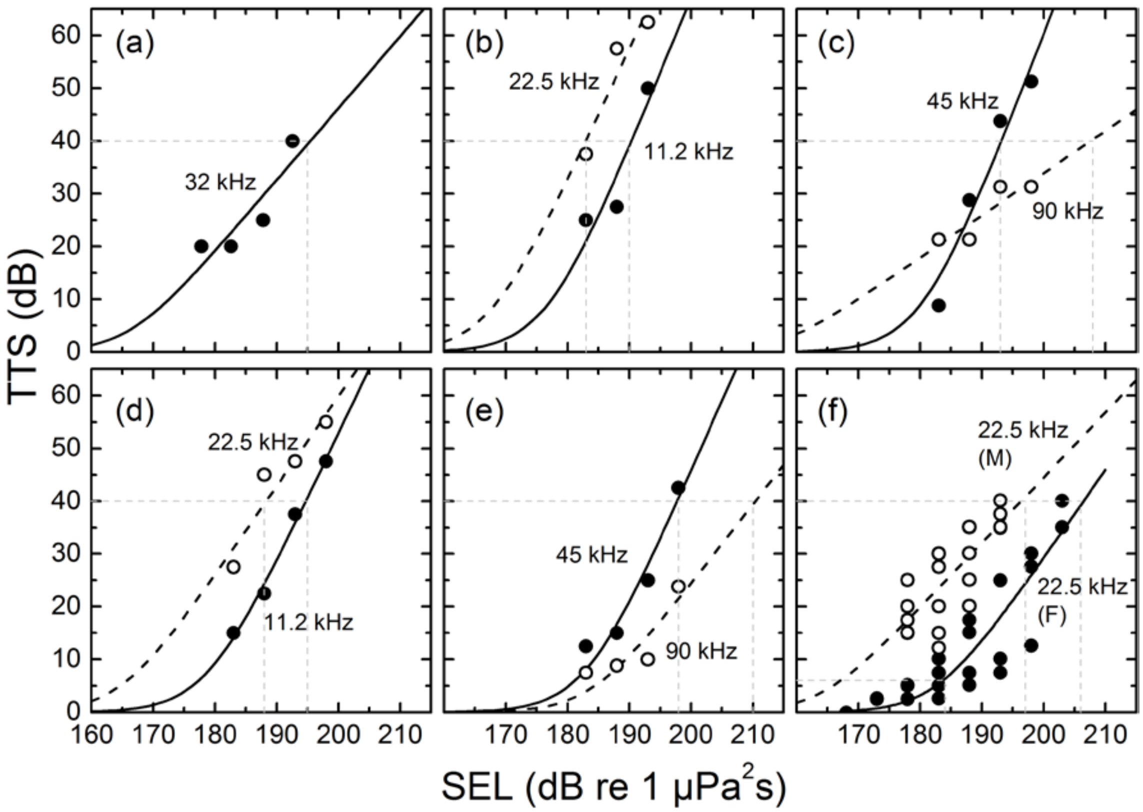

Figure A11. **TTS growth data for mid-frequency cetaceans obtained using AEP methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.**

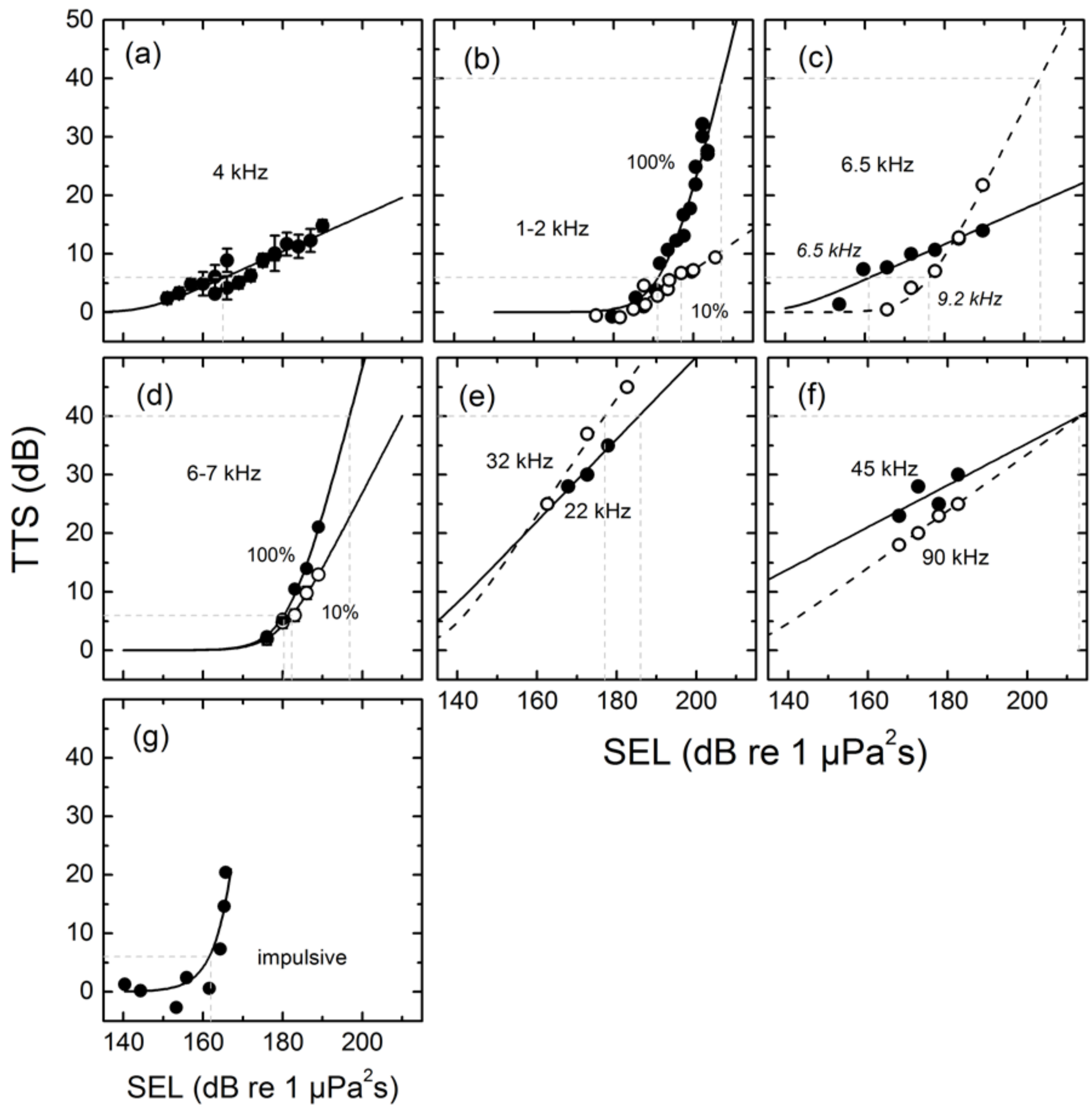

Figure A12. TTS growth data for high-frequency cetaceans obtained using behavioral and AEP methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. The exposure frequency is specified in normal font; italics indicate the hearing test frequency. Percentages in panels (b), (d) indicate exposure duty cycle (duty cycle was 100% for all others). Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.

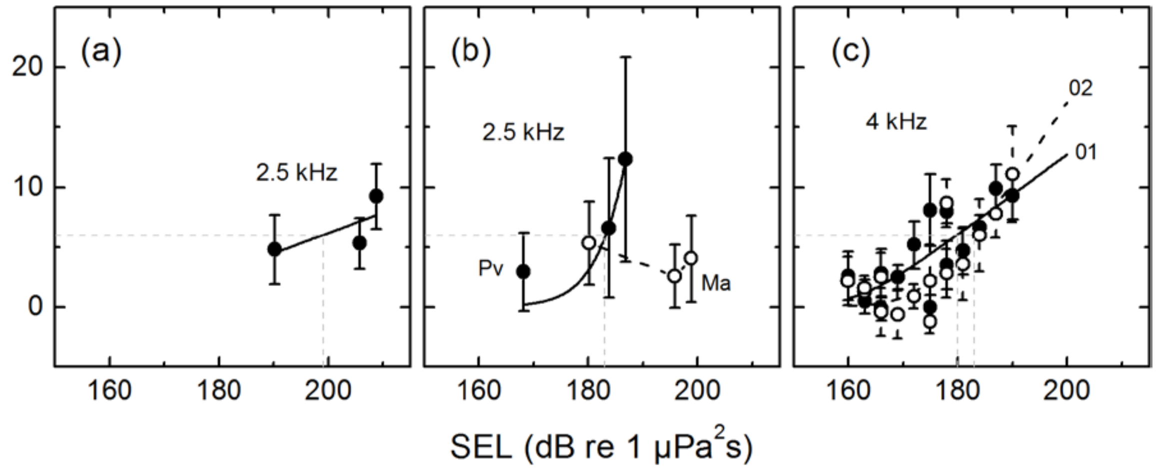

Figure A13. **TTS growth data for pinnipeds obtained using behavioral methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Frequency values within the panels indicate the exposure frequencies. Numeric values in panel (c) indicate subjects 01 and 02. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.**

Table A6. 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 μPa^{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., 2010a)	10(c)
MF	*Tursiops truncatus*	BLU	3	0	23	206*	1.0	240	34	TTS onset higher than subsequent tests	(Finneran et al., 2010b)	10(d)
MF	*Tursiops truncatus*	TYH	3	0	9	194	0.35	—	—		(Finneran et al., 2010b)	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., 2015b)	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)

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)

* 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 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 were obtained from AEP testing, or (v) a lower TTS onset was found at a different hearing test frequency (also see Notes).

** 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)

IX. TTS EXPOSURE FUNCTIONS FOR SONARS

Derivation of the weighting function parameters utilized the exposure function form described by Eq. (A2), so that the shapes of the functions could be directly compared to the TTS onset data (Table A6) 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 A5). 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).

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 A5) where the composite audiogram thresholds values were ΔT-dB above the threshold at f_0 (Fig. A14). If $\Delta T = 0$, the weighting function shape would match the shape of the inverse audiogram. Values of $\Delta T > 0$ progressively "compress" the weighting function, compared to the audiogram, near the frequency region of best sensitivity. This compression process is included to match the marine mammal TTS data, which show less change in TTS onset with frequency than would be predicted by the audiogram in the region near best sensitivity.

To determine ΔT, the exposure function amplitude defined by Eq. (A2) 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. A15). 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.

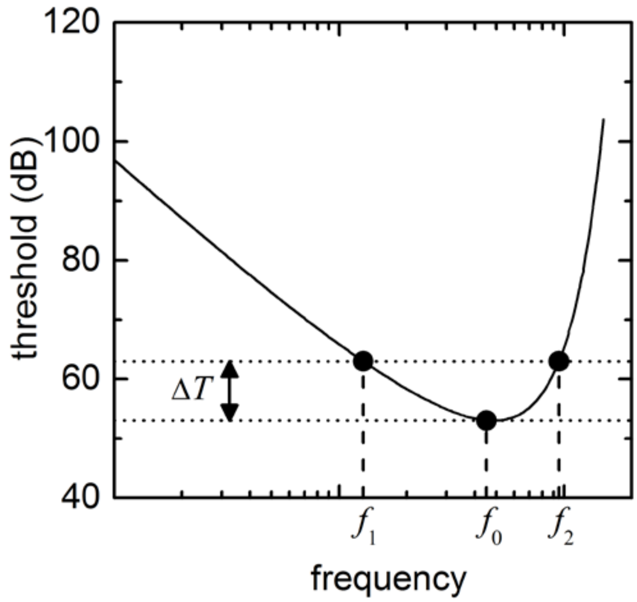

Figure A14. **The cutoff frequencies f_1 and f_2 were defined as the frequencies below and above f_0 at which the composite audiogram values were ΔT-dB above the threshold at f_0 (the lowest threshold).**

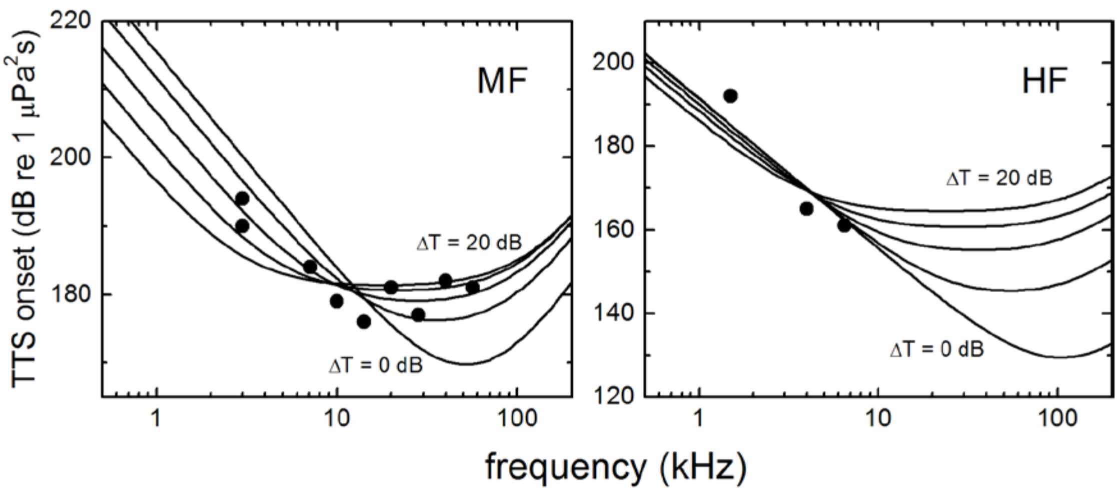

Figure A15. **Effect of ΔT adjustment on the TTS exposure functions for the mid-frequency cetaceans (left) and high-frequency cetaceans (right). To calculate the exposure functions, a and b were defined as $a = s_0/20$ and $b = 2$. ΔT was then varied from 0 to 20. At each value of ΔT, K was adjusted to minimize the squared error between the exposure function and the onset TTS data (symbols). As ΔT increases, f_1 decreases and f_2 increases, causing the pass-band of the function to increase and the function to "flatten".**

For the original and normalized data, the errors between the best-fit exposure functions and the TTS data for the MF and HF cetaceans were squared, summed, and divided by the total number of TTS data points (12). This provided an overall mean-squared error (MSE) for the original and normalized data as a function of ΔT (Fig. A16). 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 ΔT = 9 dB. **Therefore, f_1 and f_2 for the remaining species groups were defined using composite audiograms based on normalized thresholds with ΔT = 9 dB.**

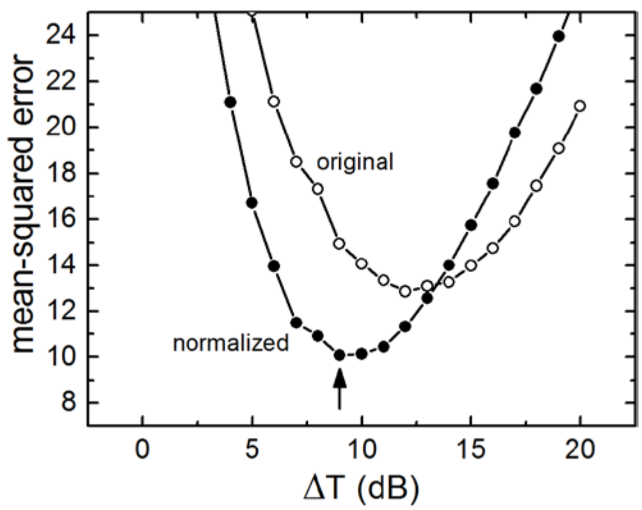

Figure A16. Relationship between ΔT and the resulting mean-squared error (MSE) between the exposure functions and onset TTS data. The MSE was calculated by adding the squared errors between the exposure functions and TTS data for the MF and HF cetacean groups, then dividing by the total number of TTS 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 ΔT = 9 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. Note that *K* is not necessarily equal to the minimum value of the exposure function.

For the low-frequency cetaceans and sirenians, 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 A7 summarizes the onset TTS and composite threshold data for the MF, HF, OW, and PW groups. For these groups, the median difference between the TTS onset and composite audiogram threshold at f_0 was 126 dB. In the absence of data, the hearing threshold at f_0 for the LF group was set equal to the median threshold at f_0 for the other groups (MF, HF, SI, OW, PW, median = 54 dB re 1 μPa). The TTS onset value at f_0 is therefore 180 dB re 1 μPa^{2}s for the low-frequency cetaceans (Table A7). For the sirenians, the lowest threshold was 61 dB re 1 μPa, making the onset TTS estimate 187 dB re 1 μPa^{2}s (Table A7).

Table A7. Differences between composite threshold values (Fig. A5) and TTS onset values at the frequency of best hearing (f_0) for the in-water marine mammal species groups. The values for the low-frequency cetaceans and sirenians were estimated using the median difference (126) from the MF, HF, OW, and PW groups.

Group	f_0 (kHz)	Threshold at f_0 (dB re 1 μPa)	TTS onset at f_0 (dB re 1 μPa^{2}s)	Difference	Estimated difference	Estimated TTS onset at f_0 (dB re 1 μPa^{2}s)
LF	5.6	54			126	180
MF	55	54	179	125		
HF	105	48	156	108		
SI	16	61			126	187
OW	12	67	199	132		
PW	8.6	53	181	128		

Once K was determined, the weighted threshold for onset TTS was determined from the minimum value of the exposure function. Finally, the constant C was determined by substituting parameters a, b, f_1, and f_2 into Eq. (A1), then adjusting C so the maximum amplitude of the weighting function was 0 dB; this is equivalent to the difference between the weighted TTS threshold and K [see Eqs. (A3)–(A8)].

Table A8 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. A17–A20.

Table A8. Weighting function and TTS exposure function parameters for use in Eqs. (A1) and (A2) for steady-state exposures. R^2 values represent goodness of fit between exposure function and TTS onset data (Table A6).

Group	a	b	f_1 (kHz)	f_2 (kHz)	K (dB)	C (dB)	Weighted TTS threshold (dB SEL)	R^2
LF	1	2	0.20	19	179	0.13	179	—
MF	1.6	2	8.8	110	177	1.20	178	0.825
HF	1.8	2	12	140	152	1.36	153	0.864
SI	1.8	2	4.3	25	183	2.62	186	—
OW	2	2	0.94	25	198	0.64	199	—
PW	1	2	1.9	30	180	0.75	181	0.557

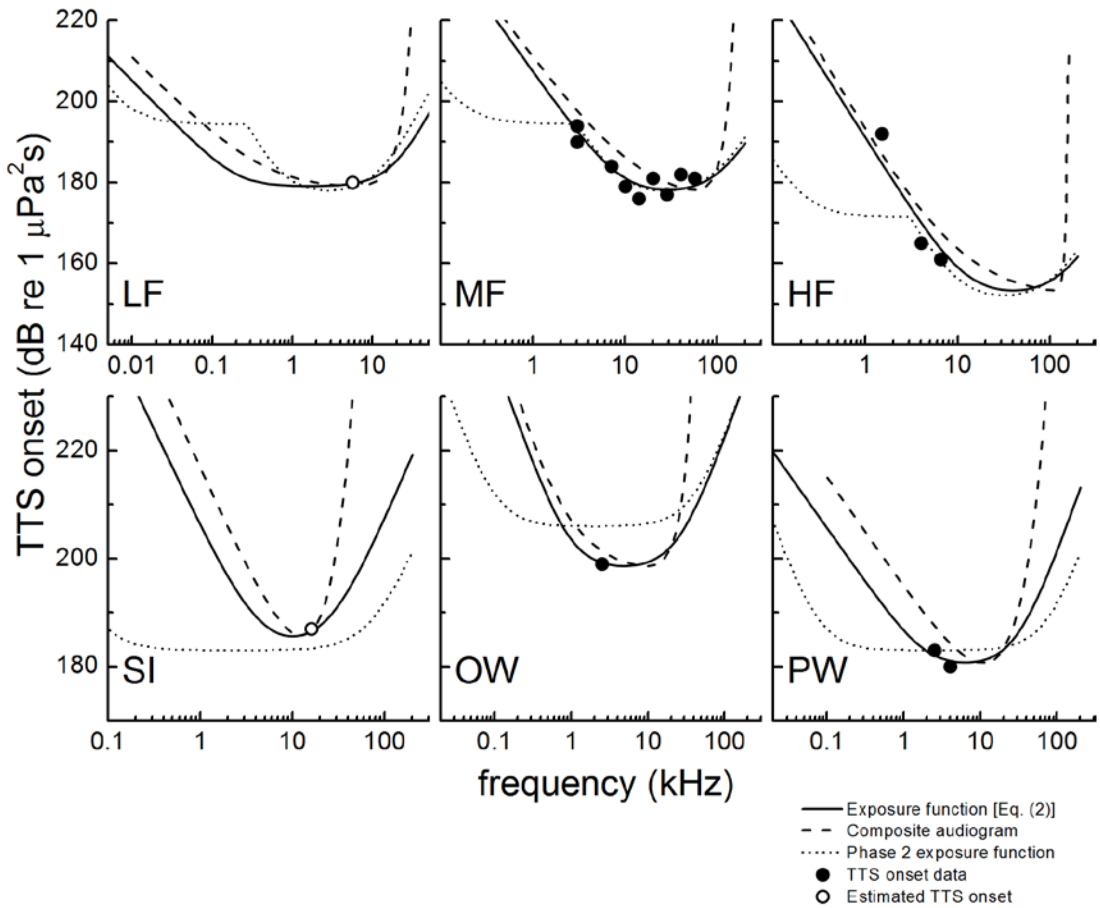

Figure A17. **Exposure functions (solid lines) generated from Eq. (A2) with the parameters specified in Table A7. Dashed lines — (normalized) composite audiograms used for definition of parameters a, f_1, and f_2. A constant value was added to each audiogram to equate the minimum audiogram value with the exposure function minimum. Short dashed line — Navy Phase 2 exposure functions for TTS onset for each group. Filled symbols — onset TTS exposure data (in dB SEL) used to define exposure function shape and vertical position. Open symbols — estimated TTS onset for species for which no TTS data exist.**

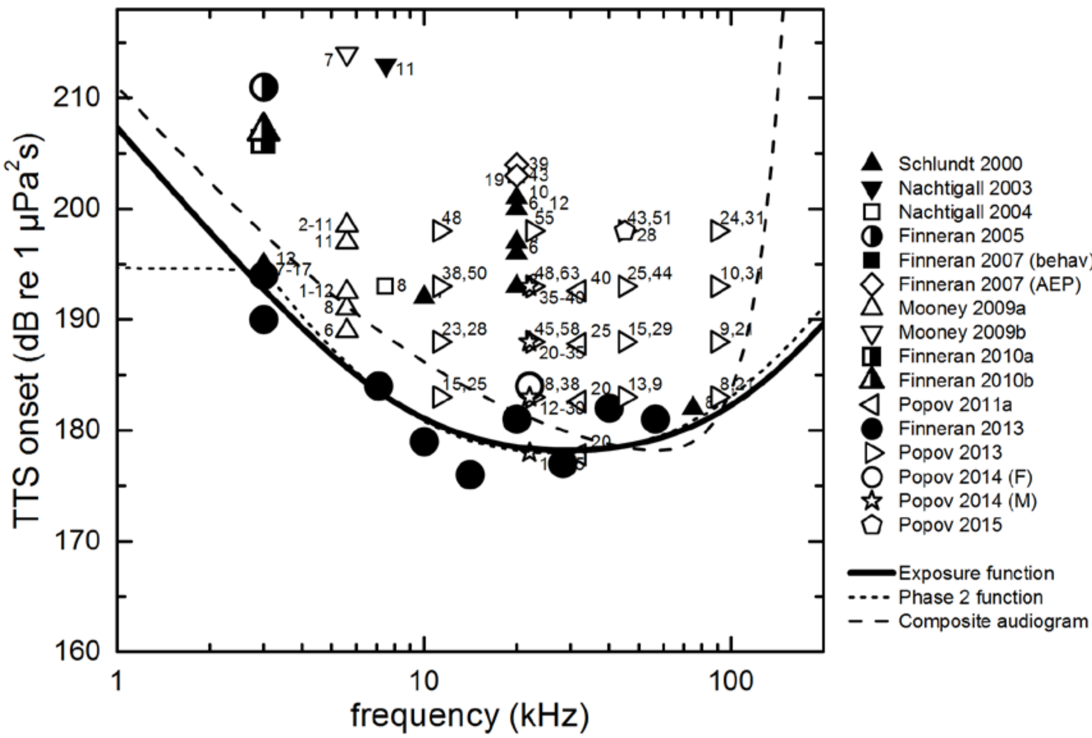

Figure A18. **Mid-frequency cetacean exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to mid-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS. Filled and half-filled symbols — behavioral data. Open symbols — AEP data.**

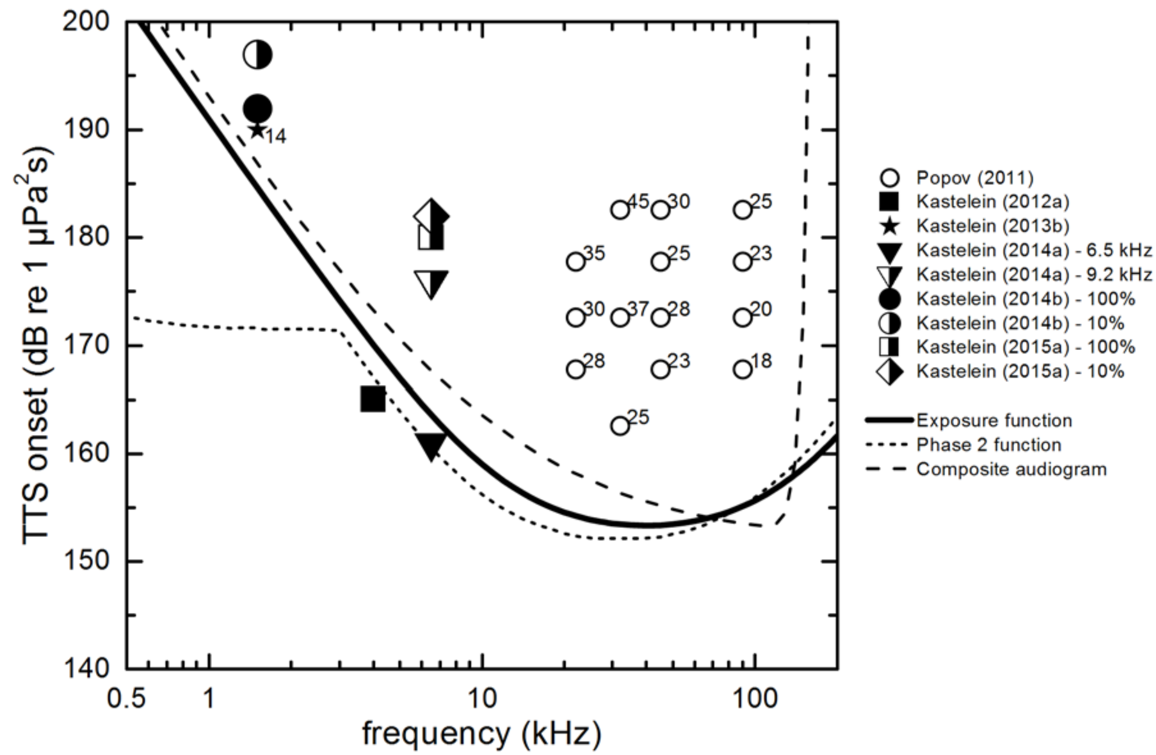

Figure A19. **High-frequency cetacean TTS exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to high-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS. Filled and half-filled symbols — behavioral data. Open symbols — AEP data.**

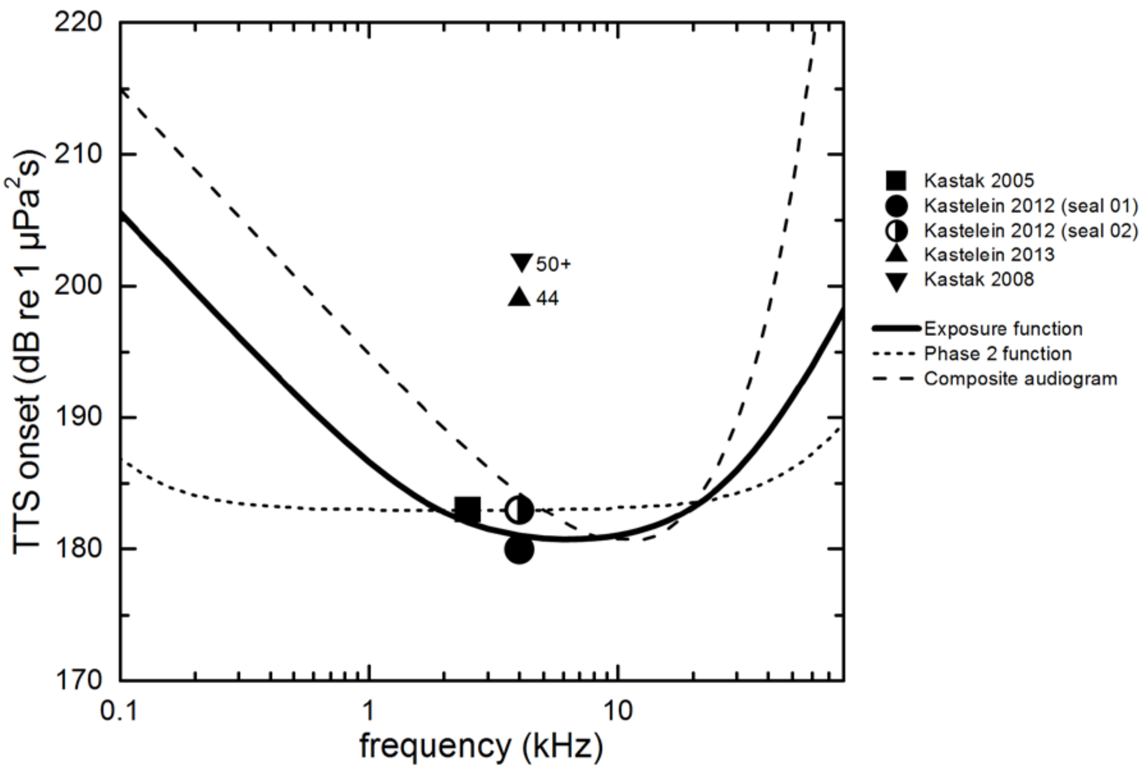

Figure A20. **Phocid (underwater) exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to phocid TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS.**

X. 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 TTS and the onset of PTS.

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, ursids, and sirenians (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 = 24, median = 22, $n = 9$) 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 A10).

XI. 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.

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 used for estimating the effects of the noise exposure.

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 A9). 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 170 and 140 dB re 1 μPa^2s for the mid- and high-frequency cetaceans, respectively (Table A9). 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 is 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. (2015c) 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 high-frequency cetacean group. Kastelein et al. (2015c) provide a representative frequency spectrum for a single, simulated pile driving strike at a specific measurement location. When the high-frequency 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 114 dB re 1 μPa^2s. For 2760 impulses, the cumulative, weighted SEL would then be 148 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 139 dB re 1 μPa^2s, which compares favorably to the high-frequency cetacean TTS threshold of 140 dB re 1 μPa^2s derived from the Lucke et al. (2009) air gun data.

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 groups for which data exist (the mid- and high-frequency cetaceans):

$$G_s - G_i = \overline{C_s} - \overline{C_i}, \tag{A11}$$

where G indicates thresholds for a species group for which impulse TTS data are not available, $\overline{C}$ indicates the median threshold for the groups for which data exist, the subscript s indicates a steady-state threshold, and the subscript i indicates an impulse threshold (note that since data are only available for the mid- and high-frequency cetaceans the median and mean are identical). Equation (A11) 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 178 and 153 dB re 1 μPa^{2}s, respectively, and the impulse TTS thresholds are 170 and 140 dB re 1 μPa^{2}s, respectively, making $\overline{C_s} - \overline{C_i}$ = 11 dB. Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 11 dB below the steady-state TTS threshold (Table A9).

To estimate peak SPL-based thresholds, Southall et al. (2007) used Eq. (A11) 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 178 and 153 dB re 1 μPa^{2}s, respectively, and the peak SPL, impulse TTS thresholds are 224 and 196 dB re 1 μPa, respectively, making $\overline{C_s} - \overline{C_i}$ = -44 dB. Based on this relationship, the peak SPL-based impulse TTS threshold (in dB re 1 μPa) would be 44 dB above the steady-state TTS threshold (in dB re 1 μPa^{2}s), making the peak SPL thresholds vary from 222 to 243 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 impulsive peak SPL thresholds are estimated using a "dynamic range" estimate based on the difference (in dB) between the impulsive noise, peak SPL TTS onset (in dB re 1 μPa) and the hearing threshold at f_0 (in dB re 1 μPa) for the groups for which data are available (the mid- and high-frequency cetaceans). For the mid-frequency cetaceans, the hearing threshold at f_0 is 54 dB re 1 μPa and the peak SPL TTS threshold is 224 dB re 1 μPa, resulting in a dynamic range of 170 dB. For the high-frequency cetaceans, the hearing threshold at f_0 is 48 dB re 1 μPa and the peak SPL-based TTS threshold is 196 dB re 1 μPa, resulting in a dynamic range of 148 dB. The median dynamic range for the mid- and high-frequency cetaceans is therefore 159 dB (since there are only two values, the mean and median are equal). For the remaining species groups, the impulsive peak SPL-based TTS thresholds are estimated by adding 159 dB to the hearing threshold at f_0 (Table A9).

Since marine mammal PTS data from impulsive noise exposures do not exist, onset-PTS levels for impulsive exposures 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.

Table A9. TTS and PTS thresholds for explosives and other impulsive sources. SEL thresholds are in dB re 1 μPa^{2}s and peak SPL thresholds are in dB re 1 μPa.

Group	Hearing threshold at f_0	TTS threshold		PTS threshold	
	SPL (dB SPL)	SEL (weighted) (dB SEL)	peak SPL (dB SPL)	SEL (weighted) (dB SEL)	peak SPL (dB SPL)
LF	54	168	213	183	219
MF	54	170	224	185	230
HF	48	140	196	155	202
SI	61	175	220	190	226
OW	67	188	226	203	232
PW	53	170	212	185	218

XII. SUMMARY

Figure A21 illustrates the shapes of the various Phase 3 auditory weighting functions. Table A10 summarizes the parameters necessary to calculate the weighting function amplitudes using Eq. (A1).

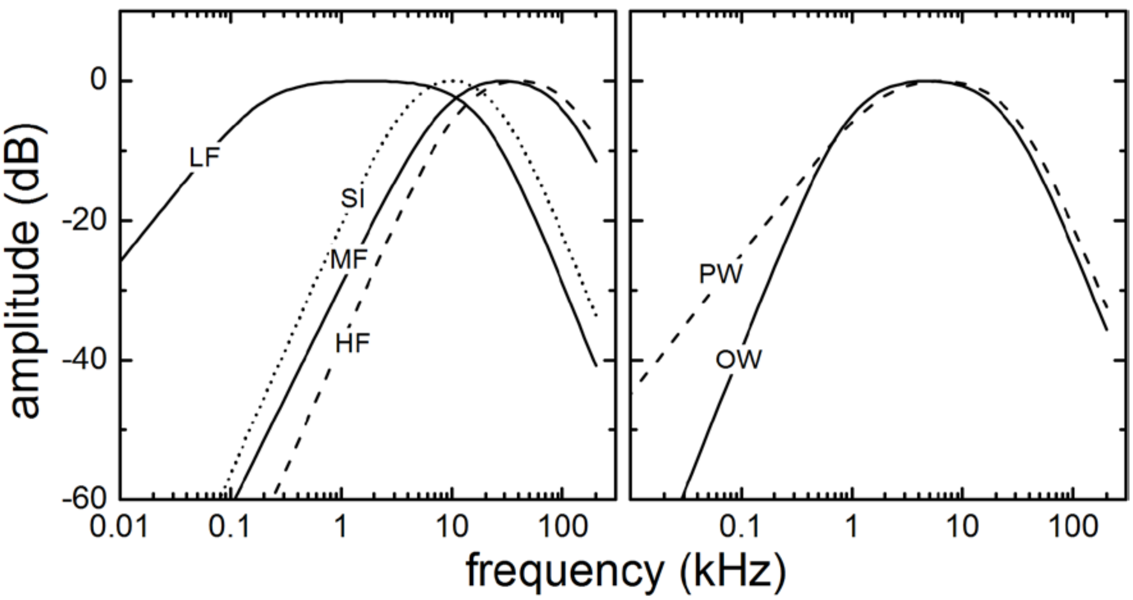

Figure A21. Navy Phase 3 weighting functions for marine mammal species groups exposed to underwater sound. Parameters required to generate the functions are provided in Table A10.

Table A10. 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.

$W(f) = C + 10\log_{10}\left\{ \frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a \left[1+(f\right.} \right.$						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	*a*	*b*	*f₁* (kHz)	*f₂* (kHz)	*C* (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

To properly compare the TTS/PTS criteria and thresholds used by Navy for Phase 2 and Phase 3, both the weighting function shape and 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). Since the 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 (Figs A22 and A23).

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

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

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

(3) Impulsive TTS/PTS thresholds near the region of best hearing sensitivity are lower for Phase 3 compared to Phase 2.

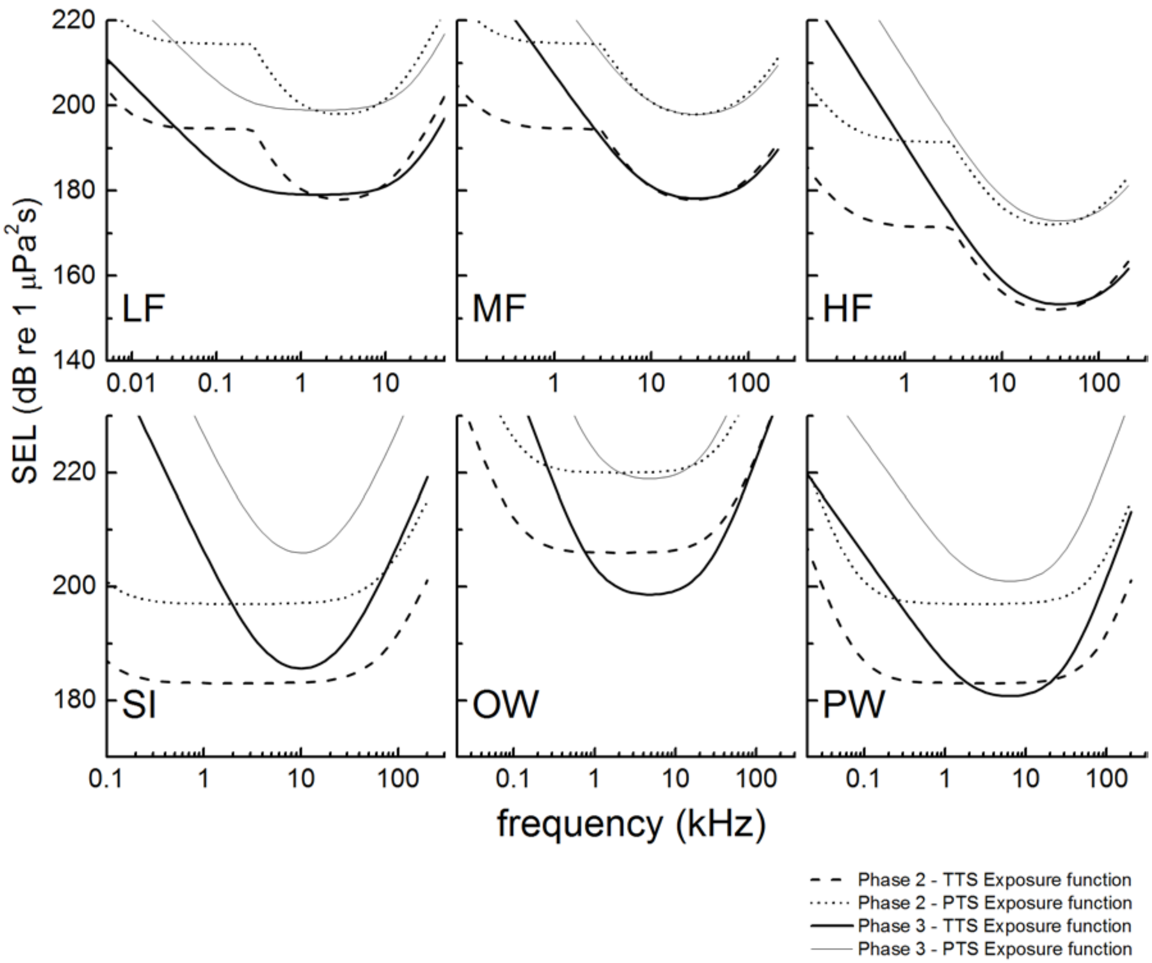

Figure A22. TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table A10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table A10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

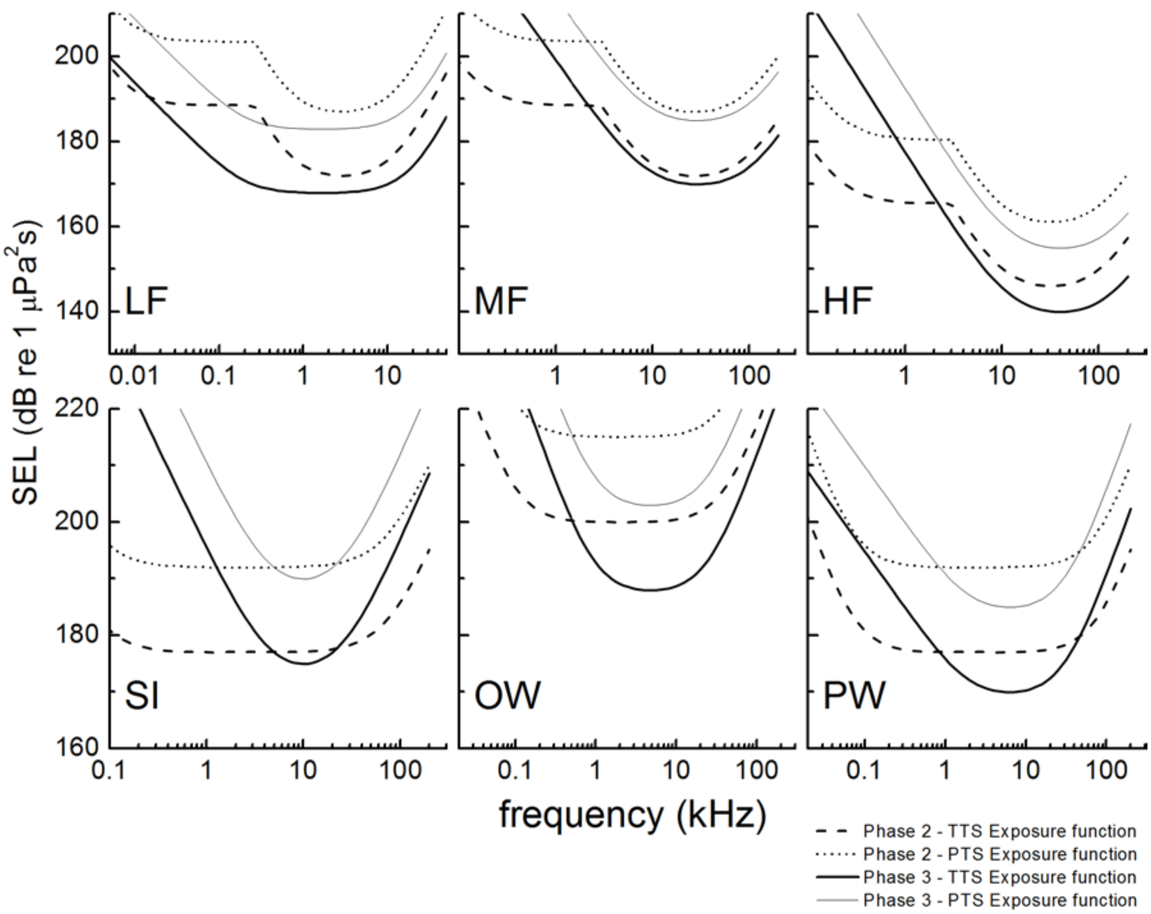

Figure A23. **TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table A10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table A10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.**

APPENDIX A1. ESTIMATING A LOW-FREQUENCY CETACEAN AUDIOGRAM

A1.1. Background

Psychophysical and/or electrophysiological auditory threshold data exist for at least one species within each hearing group, except for the low-frequency (LF) cetacean (i.e., mysticete) group, for which no direct measures of auditory threshold have been made. For this reason, an alternative approach was necessary to estimate the composite audiogram for the LF cetacean group.

The published data sources available for use in estimating mysticete hearing thresholds consist of: cochlear frequency-place maps created from anatomical measurements of basilar membrane dimensions (e.g., Ketten, 1994; Parks et al., 2007); scaling relationships between inter-aural time differences and upper-frequency limits of hearing (see Ketten, 2000); finite element models of head-related and middle-ear transfer functions (Tubelli et al., 2012; Cranford and Krysl, 2015); a relative hearing sensitivity curve derived by integrating cat and human threshold data with a frequency-place map for the humpback whale (Houser et al., 2001); and measurements of the source levels and frequency content of mysticete vocalizations (see review by Tyack and Clark, 2000). These available data sources are applied here to estimate a mysticete composite audiogram. Given that these data are limited in several regards and are quite different from the type of data supporting composite audiograms in other species, additional sources of information, such as audiograms from other marine mammals, are also considered and applied to make conservative extrapolations at certain decision points.

Mathematical models based on anatomical data have been used to predict hearing curves for several mysticete species (e.g., Ketten and Mountain, 2009; Cranford and Krysl, 2015). However, these predictions are not directly used to derive the composite audiogram for LF cetaceans for two primary reasons:

> (1) There are no peer-reviewed publications that provide a complete description of the mathematical process by which frequency-place maps based on anatomical measurements were integrated with models of middle-ear transfer functions and/or other information to derive the predicted audiograms presented in several settings by Ketten/Mountain (e.g., Ketten and Mountain, 2009). As a result, the validity of the resulting predicted audiograms cannot be independently evaluated, and these data cannot be used in the present effort.
>
> (2) Exclusion of the Ketten/Mountain predicted audiograms leaves only the Cranford/Krysl predicted fin whale hearing curve (Cranford and Krysl, 2015). However, this curve cannot be used by itself to predict hearing thresholds for all mysticetes because:

(a) The Cranford/Krysl model is based on sound transmission through the head to the ear of the fin whale, but does not include the sensory receptors of the cochlea. There is therefore no way to properly predict the upper cutoff of hearing and the shape of the audiogram at frequencies above the region of best predicted sensitivity.

(b) The audiogram does not possess the typical shape one would expect for an individual with normal hearing based on measurements from other mammals. Specifically, the "hump" in the low-frequency region and the shallow roll-off at high frequencies do not match patterns typically seen in audiometric data from other mammals with normal hearing. Given these considerations, the proposed audiogram cannot be considered representative of all mysticetes without other supporting evidence. Although the specific numeric thresholds from Cranford and Krysl (2015) are not directly used in the revised approach explained here, the predicted thresholds are still used to inform the LF cetacean composite audiogram derivation.

Vocalization data also cannot be used to directly estimate auditory sensitivity and audible range, since there are many examples of mammals that vocalize below the frequency range where they have best hearing sensitivity, and well below their upper hearing limit. However, it is generally expected that animals have at least some degree of overlap between the auditory sensitivity curve and the predominant frequencies present in conspecific communication signals. Therefore vocalization data can be used to evaluate, at least at a general level, whether the composite audiogram is reasonable; i.e., to ensure that the predicted thresholds make sense given what we know about animal vocalization frequencies, source levels, and communication range.

The realities of the currently available data leave only a limited amount of anatomical data and finite element modeling results to guide the derivation of the LF cetacean composite audiogram, supplemented with extrapolations from the other marine mammal species groups where necessary and a broad evaluation of the resulting audiogram in the context of whale bioacoustics.

A1.2. Audiogram Functional Form and Required Parameters

Navy Phase 3 composite audiograms are defined by the equation

$$T(f) = T_0 + A\log_{10}\left(1+\frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \qquad \text{(A1.1)}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are constants. To understand the physical significance and influence of the parameters T_0, F_1, F_2, A, and B, Eq. (A1.1) may be viewed as the sum of three individual terms:

$$T(f) = T_0 + L(f) + H(f), \tag{A1.2}$$

where

$$L(f) = A\log_{10}\left(1 + \frac{F_1}{f}\right), \tag{A1.3}$$

and

$$H(f) = \left(\frac{f}{F_2}\right)^B. \tag{A1.4}$$

The first term, T_0, controls the vertical position of the curve; i.e., T_0 shifts the audiogram up and down.

The second term, $L(f)$, controls the low-frequency behavior of the audiogram. At low frequencies, when $f < F_1$, Eq. (A1.3) approaches

$$L(f) = A\log_{10}\left(\frac{F_1}{f}\right), \tag{A1.5}$$

which can also be written as

$$L(f) = A\log_{10} F_1 - A\log_{10} f. \tag{A1.6}$$

Equation (A.6) has the form of $y(x) = b - Ax$, where $x = \log_{10}f$; i.e., Eq. (A.6) describes a linear function of the logarithm of frequency. This means that, as frequency gets smaller and smaller, Eq. (A.3) — the low-frequency portion of the audiogram function — approaches a linear function with the logarithm of frequency, and has a slope of $-A$ dB/decade. As frequency increases towards F_1, $L(f)$ asymptotically approaches zero.

The third term, $H(f)$, controls the high-frequency behavior of the audiogram. At low frequencies, when $f \ll F_2$, Eq. (A1.4) has a value of zero. As f increases, $H(f)$ exponentially grows. The parameter F_2 defines the frequency at which the thresholds begin to exponentially increase, while the factor B controls the rate at which thresholds increase. Increasing F_2 will move the upper cutoff frequency to the right (to higher frequencies). Increasing B will increase the “sharpness” of the high-frequency increase.

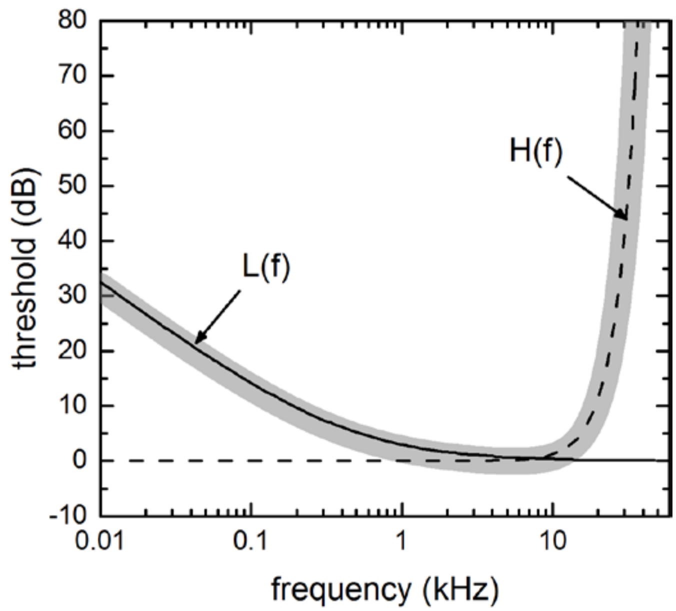

FIGURE A1.1. Relationship between estimated threshold, T(f), (thick, gray line), low-frequency term, L(f), (solid line), and high-frequency term, H(f), (dashed line).

A1.3. ESTIMATING AUDIOGRAM PARAMETERS

To derive a composite mysticete audiogram using Eq. (A1.1), the values of T_0, F_1, F_2, A, and B must be defined. The value for T_0 is determined by either adjusting T_0 to place the lowest threshold value to zero (to obtain a normalized audiogram), or to place the lowest expected threshold at a specific SPL (in dB re 1 μPa). For Navy Phase 3 analyses, the lowest LF cetacean threshold is defined to match the median threshold of the in-water marine mammal species groups (MF cetaceans, HF cetaceans, sirenians, otariids and other marine carnivores in water, and phocids in water; median = 54 dB re 1 μPa). The choices for the other parameters are informed by the published information regarding mysticete hearing.

The constant A is defined by assuming a value for the low-frequency slope of the audiogram, in dB/decade. Most mammals for which thresholds have been measured have low-frequency slopes ~30 to 40 dB/decade. However, finite element models of middle ear function in fin whales (Cranford and Krysl, 2015) and minke whales (Tubelli et al., 2012) suggest lower slopes, of ~25 or 20 dB/decade, respectively. **We therefore conservatively assume that A = 20 dB/decade.**

To define F_1, we first define the variable T' as the maximum threshold tolerance within the frequency region of best sensitivity (i.e., within the frequency range of best sensitivity, thresholds are within T' dB of the lowest threshold). Further, let f' be the lower frequency bound of the region of best sensitivity. When $f = f'$, $L(f) = T'$, and Eq. (A1.3) can then be solved for F_1 as a function of f', T', and A:

$$F_1 = f'\left(10^{T'/A} - 1\right). \tag{A1.7}$$

Anatomically-based models of mysticete hearing have resulted in various estimates for audible frequency ranges and frequencies of best sensitivity. Houser et al. (2001) estimated best sensitivity in humpback whales to occur in the range of 2 to 6 kHz, with thresholds within 3 dB of best sensitivity from ~1.4 to 7.8 kHz. For right whales, Parks et al. (2007) estimated the audible frequency range to be 10 Hz to 22 kHz. For minke whales, Tubelli et al. (2012) estimated the most sensitive hearing range, defined as the region with thresholds within 40 dB of best sensitivity, to extend from 30 to 100 Hz up to 7.5 to 25 kHz, depending on the specific model used. Cranford and Krysl (2015) predicted best sensitivity in fin whales to occur at 1.2 kHz, with thresholds within 3-dB of best sensitivity from ~1 to 1.5 kHz. Together, these model results broadly suggest best sensitivity (thresholds within ~3 dB of the lowest threshold) from ~1 to 8 kHz, and thresholds within ~40 dB of best sensitivity as low as ~30 Hz and up to ~25 kHz.

Based on this information, we assume LF cetacean thresholds are within 3 dB of the lowest threshold over a frequency range of 1 to 8 kHz, therefore T' = 3 dB and f' = 1 kHz, resulting in **F_1 = 0.41 kHz** [Eq. (A1.7)]. In other words, we define F_1 so that thresholds are ≤ 3 dB relative to the lowest threshold when the frequency is within the region of best sensitivity (1 to 8 kHz).

To define the high-frequency portion of the audiogram, the values of B and F_2 must be estimated. To estimate B for LF cetaceans, we take the median of the B values from the composite audiograms for the other in-water marine mammal species groups (MF cetaceans, HF cetaceans, sirenians, otariids and other marine carnivores in water, and phocids in water). **This results in B = 3.2 for the LF cetaceans.** Once B is defined, F_2 is adjusted to achieve a threshold value at 30 kHz of 40 dB relative to the lowest threshold. **This results in F_2 = 9.4 kHz. Finally, T_0 is adjusted to set the lowest threshold value to 0 dB for the normalized curve, or 54 dB re 1 μPa for the non-normalized curve; this results in T_0 = -0.81 and 53.19 for the normalized and non-normalized curves, respectively.**

The resulting composite audiogram is shown in Fig. A1.2. For comparison, predicted audiograms for the fin whale (Cranford and Krysl, 2015), and humpback whale (Houser et al., 2001) are included. The LF cetacean composite audiogram has lowest threshold at 5.6 kHz, but the audiogram is fairly shallow in the region of best sensitivity, and thresholds are within 1 dB of the lowest threshold from ~1.8 to 11 kHz, and within 3 dB of the lowest threshold from ~0.75 to 14 kHz. Low-frequency (< ~500 Hz) thresholds are considerably lower than those predicted by Cranford and Krysl (2015). High-frequency thresholds are also substantially lower than those predicted for the fin whale, with thresholds at 30 kHz only 40 dB above best hearing thresholds, and those at 40 kHz approximately 90 dB above best threshold. The resulting LF composite audiogram appears reasonable in a general sense relative the predominant frequencies present in mysticete conspecific vocal communication signals. While some species (e.g., blue whales) produce some extremely low (e.g., 10 Hz) frequency call components, the majority of mysticete social calls occur in the few tens of Hz to few kHz range, overlapping reasonably well with the predicted auditory sensitivity shown in the composite audiogram (within ~0 to 30 dB of predicted best sensitivity). A general pattern of some social calls containing energy shifted below the region of best hearing sensitivity is well-documented in other low-frequency species including many phocid seals (see Wartzok and Ketten, 1999) and some terrestrial mammals, notably the Indian elephant (Heffner and Heffner, 1982).

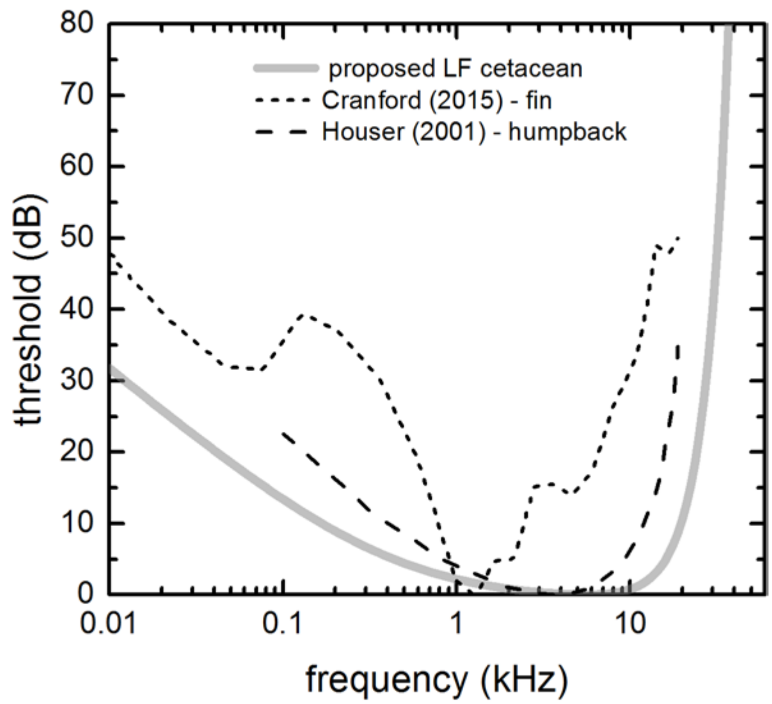

FIGURE A1.2. Comparison of proposed LF cetacean thresholds to those predicted by anatomical and finite-element models.

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APPENDIX B: RESEARCH RECOMMENDATIONS FOR IMPROVED ACOUSTIC THRESHOLDS

In compiling, interpreting, and synthesizing the scientific literature to produce updated acoustic thresholds for this Technical Guidance, it is evident that additional data would be useful for future iterations of this document, since many data gaps still exist (Table B1). The need for the Technical Guidance to identify critical data gaps was also recommended during the initial peer review and public comment period.

Table B1: Summary of currently available marine mammal data.

Hearing Group	Audiogram Data/Number of Species	TTS Data/Number of Species	Sound Sources for TTS Studies
LF Cetaceans	Predictive modeling/2 species	None/0 species	None
MF Cetaceans	Behavioral/8 species	Behavioral/2 species	Octave-band noise; Tones; Mid-frequency sonar; Explosion simulator; Watergun; Airgun
HF Cetaceans	Behavioral/2 species	Behavioral/1 species	Tones, Mid-frequency sonar; Impact pile driver; Airgun*
PW Pinnipeds	Behavioral/5 species	Behavioral/2 species	Octave-band noise; Impact pile driver
OW Pinnipeds	Behavioral/3 species	Behavioral/1 species	Octave-band noise; Arc-gap transducer

* Data collected using AEP methodology (directly incorporated in Technical Guidance, since only data set available).

Below is a list of research recommendations that NMFS 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 al. 2014;[39] Houser and Moore 2014; Lucke et al. 2014; Popper et al. 2014;[40] Williams et al. 2014; Erbe et al. 2016; Lucke et al. 2016). Note: Just because there may not be

[39] Although, Hawkins et al. 2014 identifies research gaps for fishes and invertebrates, many of the research recommendations can also be considered for other species, like marine mammals.

[40] Although, Popper et al. 2014 identifies research gaps for fishes and sea turtles, many of the research recommendations can also be considered for other species, like marine mammals.

enough information to allow for quantifiable modifications to acoustic thresholds 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, predictive models, vocalizations, taxonomy, and behavioral responses to sound). Thus, additional data[41] collected would be extremely valuable to furthering the understanding of hearing ability within this hearing group and validating other methods for approximating hearing ability. 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, predictive models based on anatomical data 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 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 hearing group as a whole. For example, are there certain species more susceptible to hearing loss from sound (i.e., all members of HF cetaceans), or are there additional delineations needed among the current hearing groups (e.g., deep diving species, etc.)? Having more data from species within a hearing group would also help identify if additional hearing groups are needed. This is especially the case for HF cetaceans where data are only available from four individuals of two species and those individuals have a lower hearing threshold compared to all other hearing groups.

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., bone conduction mechanism in mysticetes: Cranford and Krysl 2015; 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; Kastelein et al. 2005b).

[41] Data should be collected under appropriate permits or authorizations.

1.3 REPRESENTATIVENESS OF CAPTIVE INDIVIDUALS

Data from Castellote et al. (2014), from free-ranging belugas in Alaska, indicate that 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,[42] and more research is needed to examine if this trend is applicable to other species (Lucke et al. 2016).

1.3.1 Impacts of Age on Hearing

Hearing loss can result from a variety of factors beyond anthropogenic noise, including exposure to 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 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 TSs:

- 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 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 acoustic thresholds 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 authors' 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."

[42] NMFS 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, NMFS is aware that audiogram (AEP) data are often obtained during marine mammal stranding events exists, but these have yet to be published.

- 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 TSs for animals of different ages. Nevertheless, additional data are needed to confirm if these data are representative for all species (Lucke et al. 2016).

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 hearing groups (Lucke et al. 2016). For example, TTS onset acoustic thresholds for harbor porpoise (HF cetacean) are much lower compared to other odontocetes (MF cetaceans), and it would be useful to know if all HF cetaceans share these lower TTS onset acoustic thresholds or if harbor porpoises are the exception.

Recently measured underwater hearing of two captive spotted seals (Sills et al. 2014) and two captive ringed seals (Sills et al. 2015) found these species' hearing abilities are comparable to harbor seals. Thus, harbor seals, where TTS data are available, are an appropriate surrogate for ice seal species. As more data become available, this assumption will be re-evaluated.

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 mammalian 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[43]) 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, including multiple pulses/pile strikes and at frequencies below 1 kHz where most anthropogenic noise occurs) are needed.

1.5.1 Frequency and Duration of Exposure

In addition to received level, NMFS recognizes that other factors, such as frequency and duration of exposure, are also important to consider within the context of PTS onset acoustic thresholds (Table B2). However, there are not enough data to establish numerical acoustic thresholds based on these added factors (beyond what has already been included in this document, in terms of marine mammal weighting functions and SEL_{cum} thresholds). When more data become available, it may be possible to incorporate these factors into quantitative assessments.

Further, it has been demonstrated that exposure to lower-frequency broadband sounds has the potential to cause TSs at higher frequencies (e.g., Lucke et al. 2009; Kastelein et al. 2015a; Kastelein et al. 2016). The consideration of duty cycle (i.e., energy per unit time) is another important consideration in the context of exposure duration (e.g., Kastelein et al. 2015b). Having a better understanding of these phenomena would be helpful.

1.5.2 Multiple Sources

Further, a better understanding of the effects of multiple sources and multiple activities on TS, as well as 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 NIHL (e.g., Ahroon et al. 1993).

[43] More recent studies (e.g., Lucke et al. 2009; Mooney et al. 2009b; Kastelein et al. 2014a; Kastelein et al. 2014b; Kastelein et al. 2015a; Kastelein et al. 2015b; Finneran et al. 2015; Kastelein et al. 2016) have used exposures from more realistic sources, like airguns, impact pile drivers, or tactical sonar.

Table B2: Additional factors for consideration (frequency and duration of exposure) in association with PTS onset acoustic thresholds.

I. Frequency*: General Trend Identified: 1) Growth of TS: Growth rates of TS (dB of TTS/dB noise) are higher for frequencies where hearing is more sensitive (e.g., Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2014a; Kastelein et al. 2015b)
II. Duration: General Trends Identified: 1) Violation of EEH: Non-impulsive, intermittent exposures require higher SEL_{cum} to induce a TS compared to continuous exposures of the same duration (e.g., 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} (e.g., Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein et al. 2012b) 3) Recovery from a TS: With the same SEL_{cum}, longer exposures require longer durations to recover (e.g., 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 (e.g., Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b)
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; Chen et al. 2007; Lucke et al. 2016)
* Frequency-dependent hearing loss and overall hearing ability within a hearing group is taken into account, quantitatively, with auditory weighting functions. [+] Note: NMFS is currently supporting a National Academies project entitled "Assessment of the Cumulative Effects of Anthropogenic Stressors on Marine Mammals" to better address this issue (https://www8.nationalacademies.org/cp/projectview.aspx?key=49715). NOAA is also in the process of developing an agency Ocean Noise Strategy Roadmap, which includes examining the acute, chronic, and cumulative effects of noise. (http://cetsound.noaa.gov/ons).

1.5.3 Possible 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 dolphin and a beluga (Nachtigall et al. 2016a). Further studies showed that conditioning is associated with the frequency of the warning signal (Nachtigall and Supin 2015), as well as if an animal is able to anticipate when a loud sound is expected to occur after a warning signal (Nachtigall et al. 2016b).

Additionally, Finneran et al. (2015) observed two of the three dolphins in their study 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. Recently, Popov et al. (2016) investigated the impact of prolonged sound stimuli (i.e., 1500 s continuous pip successions vs. 500-ms pip trains) on the beluga auditory system and found that auditory adaptation occurred during exposure (i.e., decrease in amplitude of rate following response associated with evoked potentials) at levels below which TTS onset would likely be induced. The amount of amplitude reduction depended on stimulus duration, with higher reductions occurring during prolonged stimulation. The authors also caution that adaptation will vary with sound parameters.

In the wild, potential protective mechanisms have been observed, with synchronous surfacing associated with exposure to playbacks of tactical sonar recorded in long-finned pilot whales(Miller et al. 2012). However, it is unclear how effective this behavior is in reducing received levels (Wensveen et al. 2015).

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.

1.5.4 Long-Term Consequences of Exposure

Kujawa and Liberman (2009) found that with large, but recoverable noise-induced thresholds shifts (maximum 40 dB TS measured by auditory brainstem response (ABR)), sound could cause delayed cochlear nerve degeneration in mice. Further, Lin et al. (2011) reported a similar pattern of neural degeneration in mice after large but recoverable noise-induced TSs (maximum ~50 dB TS 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 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). Heeringa and van Dijk (2014) reported firing rates in the inferior colliculus of guinea pigs had a different recovery pattern compared to ABR thresholds. Thus, it is recommended that there be additional studies to look at these potential effects in marine mammals (Tougaard et al. 2015).

Finally, 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). For example, occupational noise standards, such as those from the Occupational Safety & Health Administration (OSHA), consider the impact of noise exposure over a life-time of exposure (e.g., 29 CFR Part 1926 over 40 years). Similar, longer-term considerations are needed for marine mammals.

1.6 IMPACTS OF NOISE-INDUCED 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, 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 TS 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 a long enough duration or to a high enough level to induce a TS (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 TSs 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 TS, it is important to consider the magnitude of the TS, 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). 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 2015). 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., substituting "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 TSs (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 these reactions, especially in terms of exposure conditions having the potential to cause NIHL is critical to be able to predict exposure better. Understanding marine mammal responses to anthropogenic sound exposure presents a set of unique challenges, which arise from the inherent complexity of behavioral reactions. 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 behavioral responses can also vary depending on characteristics associated with the sound source (e.g., whether it is moving or stationary, number of sound sources, distance from the source) or the potential for the source and individuals to co-occur 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) (Richardson et al. 1995; NRC 2003; Wartzok et al. 2004; NRC 2005; Southall et al. 2007; Bejder et al. 2009).

Further, 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 behaviorally sensitive species) that make a species or individuals of that species more or less likely to react to anthropogenic sound. Having this information would be useful in improving the recommended accumulations period (i.e., 24 h) and understanding situations where individuals are more likely to be exposed to noise over longer durations and are more at risk for NIHL, either temporary or permanent.

1.8 Characteristics of Sound Associated with NIHL 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 a better understanding as to how sounds could possess less injurious characteristics further from the source (e.g., transition range).

Further, validation and/or comparison of various propagation and exposure models for a variety of sources would be useful to regulators, who with more complex acoustic thresholds will be faced with evaluating the results from a multitude of models. This would also allow for a more complete comparison to the methodologies provided in this Technical Guidance. This would allow for a determination of how precautionary these methodologies are under various scenarios and allow for potential refinement.

1.9 Noise-Induced Threshold Shift Growth Rates and Recovery

TS growth rate data for marine mammals are limited, with higher growth rates for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2015b). 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, including how long after noise exposure recovery is likely to occur, could also improve the recommended baseline accumulation period.

1.10 METRICS AND TERMINOLOGY

Sound can be described using a variety of metrics, with some being more appropriate for certain 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 thresholds and predicting impacts to hearing would be useful in confirming the value of providing dual metric thresholds using the PK and SEL_{cum} metrics for impulsive sources. As science advances, additional or more appropriate metrics may be identified and further incorporated by NMFS. 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.

Further, the Technical Guidance's acoustic thresholds are based on the EEH, which is known to be inaccurate in some situations. Recently, Popov et al. 2014 suggested that RMS 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) within the context of the Technical Guidance, NMFS often found difficulties due to lack of universally accepted standards and common terminology. Within the Technical Guidance, NMFS has tried to adopt terminology, definitions, symbols, and abbreviations that reflect those of the American National Standards Institute (ANSI). However, none of these standards are specific for underwater sound.[44] Thus, NMFS encourages the further development of appropriate standards for marine application.

1.11 EFFECTIVE QUIET

"Effective quiet" is defined as the maximum sound pressure level that will fail to produce any significant TS 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 TS are extremely low or nonexistent) in terms of hearing loss[45] (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 thresholds 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 exceed current SEL_{cum} acoustic thresholds, when the likelihood of an actual TS 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).

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[44] NMFS is aware of a draft international standard addressing underwater acoustic terminology (ISO/DIS 18405) and will further examine this standard, once it becomes final.

[45] 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).

Currently, defining effective quiet for marine mammals is not possible due to lack of data. However, a recent study by Popov et al. 2014 on belugas exposed to half-octave noise centered at 22.5 kHz indicates that effective quiet for this exposure scenario and species might be around 154 dB. In Finneran's (2015) recent review of NIHL in marine mammals, effective quiet is predicted to vary by species (e.g., below 150 to 160 dB for bottlenose dolphins and belugas; below 140 dB for Yangtze finless porpoise; 124 dB for harbor porpoise; and 174 dB for California sea lions).

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 NIHL, as well as the potential of low-level (e.g., Coping et al. 2014; Schuster et al. 2015), continuously operating sources (e.g., alternative energy tidal, wave, or wind turbines) to induce noise-induced hearing loss.

1.12 TRANSLATING BIOLOGICAL COMPLEXITY INTO PRACTICAL APPLICATION

Although, not a specific research recommendation, practical application of science is an important consideration. As more is learned about the potential effects of sound on marine mammals, the more complex future acoustic thresholds are likely to become. For example, before this Technical Guidance, NMFS primarily relied on two generic thresholds for assessing auditory impacts, with one for cetaceans (SPL RMS 180 dB) and one for pinnipeds (SPL RMS 190 dB). In this document, these two simple thresholds have now been replaced by ten PTS onset thresholds (with dual metrics for impulsive sounds), including the addition of auditory weighting functions. Although, these updated acoustic thresholds 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 a critical need.

Additionally, there is always a need for basic, practical acoustic training opportunities for action proponents and managers (most acoustic classes available are for students within an academic setting and not necessarily those who deal with acoustics in a more applied manner). Having the background tools and knowledge to be able to implement the Technical Guidance is critical to this document being a useful and effective tool in assessing the effects of noise on marine mammal hearing.

APPENDIX C: 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[46] (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). Further, 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 Technical Guidance was considered a Highly Influential Scientific Assessments (HISA),[47] 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 Technical Guidance consisted of three independent reviews covering various aspects of the document: 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 Finneran Technical Report (Finneran 2016; See Appendix A), and 3) 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 proposed application of impulsive and non-impulsive PTS acoustic thresholds based on physical characteristics at the source and how those characteristics change with range.[48]

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

[47] "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).

[48] Note: Upon evaluation of public comment received during the Technical Guidance's second public comment period (July 2015), NMFS decided to postpone implementing this methodology until more data were available to support its use.

Upon completion of the three peer reviews, NMFS was required to post and respond to all peer reviewer comments received via three separate Peer Review Reports.

1.1 INITIAL PEER REVIEW (ASSOCIATED WITH 2013 DRAFT GUIDANCE)

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 volunteered, had no conflicts of interest, had the appropriate area of expertise,[49] and were available to complete an individual review (Table C1). The focus of the peer review was on the scientific/technical studies that have been applied and the manner that they have been applied in this document.

Table C1: 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 NMFS' 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 (REVIEW OF THE FINNERAN TECHNICAL REPORT)

For their Phase 3 Acoustic Effects Analysis, the U.S. Navy provided NMFS with a technical report, by Dr. James Finneran, 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.

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

Upon evaluation, NMFS preliminarily determined that the proposed methodology, within the Finneran Technical Report (Finneran 2016), reflected the scientific literature and decided to incorporate it into the Technical Guidance. Before doing so, we commissioned an independent peer review of the Finneran Technical Report (i.e. second peer review). Note: Reviewers were not asked to review the entire Technical Guidance document.

For the second peer review (March to April 2015), NMFS 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[50] specifically in marine mammal hearing (i.e., behavior and/or AEP) and/or noise-induced hearing loss. Of the twelve nominated reviewers, four volunteered, had not conflicts of interest, had the appropriate area of expertise, and were available to complete an individual review of the Finneran Technical Report (Table C2).

Table C2: 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)
* Affiliation during initial review (Affiliation during follow-up peer review: The University of Texas at Dallas)	

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

1.2.1 Follow-Up to Second Peer Review

Concurrent with the Technical Guidance's third public comment period (see Section 2.3 of this appendix), a follow-up peer review was conducted. The focus of this peer review was whether the 2016 Proposed Changes to the Technical Guidance, associated with the third public comment period, would substantially change any of the peer reviewers' comments provided during their original review (i.e., peer reviewers were not asked to re-review the Finneran Technical Report). Additionally, peer reviewers were not asked to comment on any potential policy or legal implications of the application of the Technical Guidance, or on the

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

amount of uncertainty that is acceptable or the amount of precaution that should be embedded in any regulatory analysis of impacts.

All four previous peer reviewers were available to perform the follow-up peer review. Peer reviewers' comments and NMFS' responses to the comments, from this follow-up peer review, can be found at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

1.3 THIRD PEER REVIEW (REVIEW OF TRANSITION RANGE METHODOLOGY)

During the Technical Guidance's initial public comment period, NMFS received numerous comments relating to how the Technical 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 NMFS' categorization may not be fully reflective of real-world scenarios. Thus, NMFS 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 Technical Guidance's proposed application of impulsive and non-impulsive PTS acoustic thresholds based on physical characteristics at the source and how those characteristics change with range (i.e., transition range). Note: Reviewers were not asked to review the entire Technical Guidance document.

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 volunteered, were available, had no conflicts of interest, and had the appropriate area of expertise[51] to complete an individual review of the technical section (Table C3).

Additionally, NMFS 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, NMFS re-evaluated peer reviewer nominees previously made by the MMC for the first and second peer reviews. From this list, two reviewers volunteered, were available, had no conflicts of interest, and had the appropriate area of expertise to serve as peer reviewers (Table C3).

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

Table C3: 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 NMFS' responses to the comments, from the third peer review, can be found at: http://www.cio.noaa.gov/services_programs/prplans/ID43.html.

Note: In response to public comments made during the second public comment period, NMFS decided to withdraw its proposed transition range methodology until more data can be collected to better support this concept (i.e., see Appendix B: Research Recommendations).

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 NMFS influential scientific information (ISI) or HISA 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.

The following website contains information on the peer review process including: the charge to peer reviewers, peer reviewers' names, peer reviewers' individual reports, and NMFS' 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, NMFS recognizes the importance of feedback from action proponents/stakeholders and 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 NMFS' policy decisions under the various applicable statutes. The first two public comment periods were held after the peer review to ensure the public received the most scientifically sound product for review and comment. A third public focused comment period was held after incorporation of recommendations made by NMFS and Navy scientists (SSC-PAC) during further evaluation of the Finneran Technical Report after the second public comment period. During this third public comment period, there was a concurrent follow-up peer review. See section 1.2.1 above.

2.1 Initial Public Comment Period (Associated with 2013 Draft Technical Guidance)

A public meeting/webinar was held to inform interested parties and solicit comments on the first publicly available version of the Draft Technical 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 days, opening 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[52] 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; eight state/federal/international government agencies; two Alaskan native groups; seven industry groups; five individual subject matter experts; a scientific professional organization; 12 non-governmental organizations; an environmental consulting firm; and a regulatory watchdog group. Each provided substantive comments addressing technical aspects or issues relating to the implementation of updated acoustic thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.[53]

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

[52] Of this number, one comment was directed to the Federal Communications Commission (i.e., not meant for the Technical 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.

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

comment period was granted). The remaining 89 comments were not directly applicable to the Technical 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.

NMFS' responses to substantive comments made during the initial public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

2.2 Second Public Comment Period (Associated with 2015 Draft Technical Guidance)

Because of the significant changes made to the Draft Technical Guidance from the two additional peer reviews, NMFS proposed a second 45-day public comment, which occurred in the summer of 2015. Notice of this public comment period was published in the Federal Register on July 31, 2015, and closed September 14, 2015 (NMFS 2015).

2.2.1 Summary of Public Comments Received

A total of 20 comments were received from individuals, groups, organizations, and affiliations in the form of a letter 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: two federal agencies; four industry groups; seven subject matter experts; a scientific professional organization; seven non-governmental organizations; two Alaskan native groups; an environmental consulting firm; and a regulatory watchdog group. Each provided substantive comments addressing technical aspects and/or issues relating to the implementation of updated acoustic thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.

Of those not mentioned above, an additional four comments were submitted in the form of a letter or individual comment. One of these comments specifically requested an extension of the 45-day public comment period, while the remaining three comments were not directly applicable to the Technical 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.

NMFS responses to substantive comments made during the second public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

2.3 Third Public Comment Period (Associated with 2016 Proposed Changes From Draft Technical Guidance)[54]

While NMFS was working to address public comments and finalize the Technical Guidance, after the second public comment period, the Finneran Technical Report was further evaluated internally by NMFS, as well as externally by Navy scientists (SSC-PAC). As a result, several recommendations/modifications were suggested.

The recommendations included:

- Modification of methodology to establish predicted the composite audiogram and weighting/exposure functions for LF cetaceans

- Modification of the methodology used to establish auditory acoustic thresholds for LF cetaceans

- Movement of the white-beaked dolphin (*Lagenorhynchus albirostris*) from MF to HF cetaceans[55]

- Inclusion of a newly published harbor porpoise audiogram (HF cetacean) from Kastelein et al. 2015c

- The exclusion of multiple data sets, based on expert evaluation, from the phocid pinniped weighting function

- Removal of PK acoustic thresholds for non-impulsive sounds

- Use of dynamic range to predict PK acoustic thresholds for hearing groups where impulsive data did not exist.

After consideration of these recommendations, NMFS proposed to update the Draft Technical Guidance to reflect these suggested changes and solicited public comment on the revised sections of the document via a focused 14-day public comment period. This public comment period was advertised via the Federal Register and opened on March 16, 2016, and closed March 30, 2016 (NMFS 2016).

[54] Concurrent with this third public comment period, NMFS requested that the peer reviewers of the Finneran Technical Report review the Draft Technical Guidance's proposed changes and indicate if the revisions would significantly alter any of the comments made during their original review (i.e., follow-up to second peer review).

[55] Upon re-evaluation and considering comments made during the third public comment period, it was decided this move was not fully supported (i.e., move not supported to the level of that of the other two species in this family). Thus, this species remains a MF cetacean.

2.3.1 Summary of Public Comments Received

A total of 20[56] comments were received from individuals, groups, organizations, and affiliations in the form of a letter 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: two federal agencies; seven industry groups; three subject matter experts; a scientific professional organization; and nine non-governmental organizations. Each provided substantive comments addressing technical aspects and/or issues relating to the implementation of updated acoustic thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.

Of those not mentioned above, an additional comment was submitted from a member of the public in the form of an individual comment. Three of these comments specifically requested an extension[57] of the 14-day public comment period. Specific comments can be viewed on Regulations.gov: http://www.regulations.gov/#!docketDetail;D=NOAA-NMFS-2013-0177.

NMFS responses to substantive comments made during the third public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance: [http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.](http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm)

2.4 CHANGES TO TECHNICAL GUIDANCE AS A RESULT OF PUBLIC COMMENTS

Public comment provided NMFS with valuable input during the development of the Technical Guidance. As a result of public comments, numerous changes were incorporated in the Final Technical Guidance, with the most significant being:

- Re-examination and consideration of LF weighting function and thresholds throughout the public comment process

- Updated methodology (dynamic range) for approximating PK acoustic thresholds for species where TTS data from impulsive sources were not available

- Removal of PK acoustic thresholds for non-impulsive sources

- Addition of an appendix providing research recommendations

- Adoption of a consistent accumulation period (24-h)

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[56] One group of commenters experienced difficulty in submitting their public comments via regulations.gov. As a result, their duplicate comments were submitted three times and were counted toward this total of 20 public comments.

[57] The majority of the 20 comments received requested an extension of the public comment period. Three comments were from industry groups that only requested an extension and never provided additional comments (i.e., others in additional to requesting an extension provided substantive comments).

- More consistent means of defining generalized hearing range for each marine mammal hearing group based on ~65 dB threshold from the normalized composite audiogram.

- Modification to reflect ANSI standard symbols and abbreviations.

- Withdraw of the proposed transition range methodology (July 2015 Draft) until more data can be collected to better support this concept. Instead, this concept has been moved to the Research Recommendations (Appendix B).

- Replacement of alternative acoustic thresholds with weighting factor adjustments (WFAs) that more accurately allow those incapable of fully implementing the auditory weighting functions to implement this concept (Technical Guidance; Appendix D).

APPENDIX D: ALTERNATIVE METHODOLOGY

I. INTRODUCTION

This Appendix is provided to assist action proponents in the application of the updated acoustic thresholds presented in this Technical Guidance. Since the adoption of NMFS' 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; Finneran 2016) making it necessary to re-examine the current state of science and our acoustic thresholds. However, NMFS recognizes in updating our acoustic thresholds to reflect the scientific literature, they have become more complex.

This Appendix provides a set of alternative tools, examples, and weighting factor adjustments (WFAs) to allow action proponents with different levels of exposure modeling capabilities to be able to accurately apply NMFS' updated acoustic thresholds for the onset of PTS for all sound sources.

Note: The alternative methods, within this Appendix, include multiple conservative assumptions and therefore would be expected to typically result in higher estimates of instances of hearing impairment. The larger the scale of the activity, the more these conservative overestimates would be compounded if the alternative methodologies were used.

II. WEIGHTING FACTOR ADJUSTMENT ASSOCIATED WITH SEL_{CUM} ACOUSTIC THRESHOLDS

Numerical criteria presented in the Technical Guidance consist of both an acoustic threshold and auditory weighting function associated with the SEL_{cum} metric. NMFS 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, NMFS has developed simple weighting factor adjustments (WFA) for those who cannot fully apply auditory weighting functions associated with the SEL_{cum} metric.

WFAs consider marine mammal auditory weighting functions by focusing on a single frequency. This will typically result in similar, if not identical, predicted exposures for narrowband sounds or higher predicted exposures for broadband sounds, since only one frequency is being considered, compared to exposures associated with the ability to fully incorporate the Technical Guidance's weighting functions.

WFAs use the same acoustic thresholds contained in the Technical Guidance and allow for adjustments to be made for each hearing group based on source-specific information.

NMFS has provided a companion User Spreadsheet to help action proponents incorporate WFAs to determine isopleths for PTS onset associated with their activity: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm.

2.1 Application for Narrowband Sounds

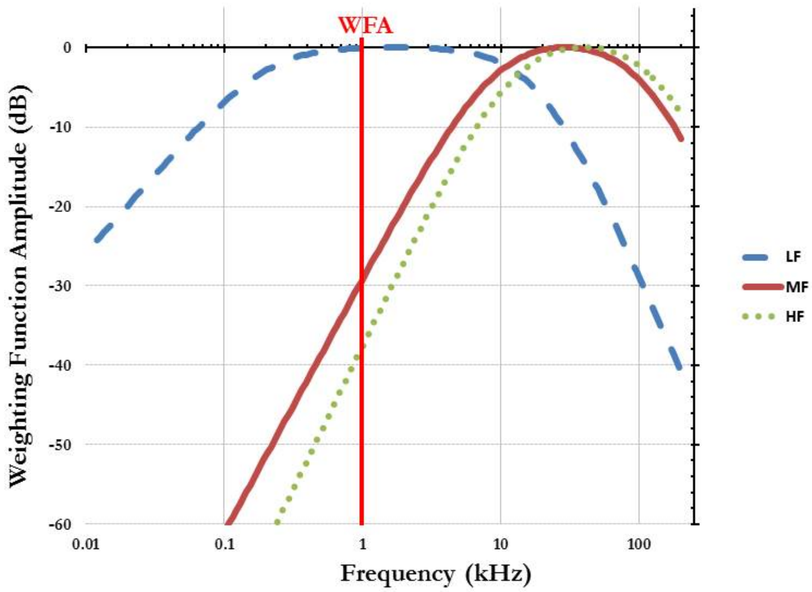
For narrowband sources, the selection of the appropriate frequency for consideration associated with WFAs is fairly straightforward. WFAs for a narrowband sound would take the weighting function amplitude, for each hearing group, associated with the particular frequency of interest and use it to make an adjustment to better reflect the hearing's group susceptibility to that narrowband sound.

As an example, a 1 kHz narrowband sound would result in the following WFAs:

- LF cetaceans: -0.06 dB
- MF cetaceans: -29.11 dB
- HF cetaceans: -37.55 dB
- Phocid pinnipeds: -5.90 dB
- Otariid pinnipeds: -4.87 dB

As this example illustrates, WFAs always result in zero or a negative dB amplitude. Additionally, the more a sound's frequency is outside a hearing group's most susceptible range (most susceptible range is where the weighting function amplitude equal zero), the more negative WFA that results (i.e., in example above 1 kHz is outside the most susceptible range for MF and HF cetaceans but in the most susceptible range for LF cetaceans; Figure D1). Further, the more negative WFA that results will lead to a smaller effect distance (isopleth) compared to a less negative or zero WFA. In other words, considering an identical SEL_{cum} acoustic threshold, a more negative WFA (i.e., source outside most susceptible frequency range) will result in a smaller effect distance (isopleth) compared to one that is less negative or closer to zero (i.e., source inside most susceptible frequency range; Figure D2).

Note: Action proponents should be aware and consider that sources may not always adhere to manufacturer specifications and only produce sound within the specified frequency (i.e., often sources are capable of producing sounds, like harmonics and subharmonics, 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 NMFS.



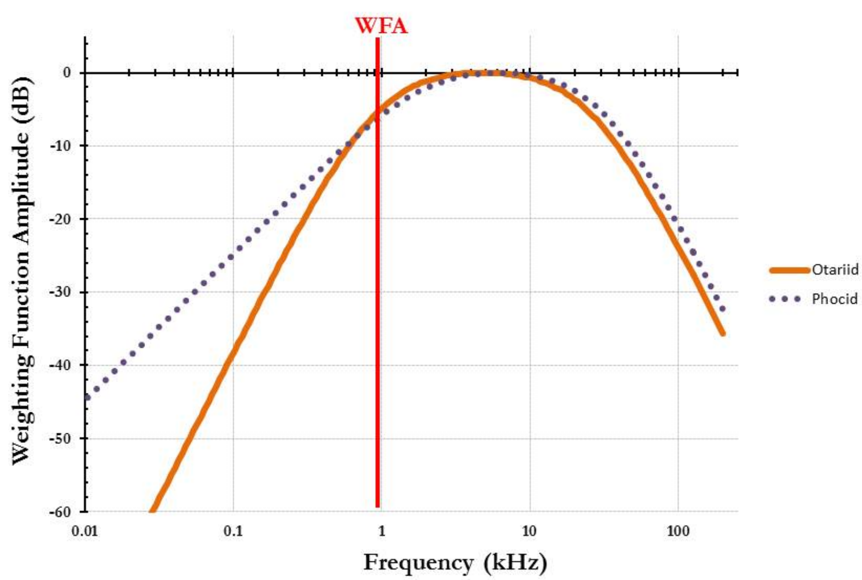


Figure D1: Example illustrating concept of weighting factor adjustment at 1 kHz (red line) with cetacean (top) and pinniped (bottom) auditory weighting functions.

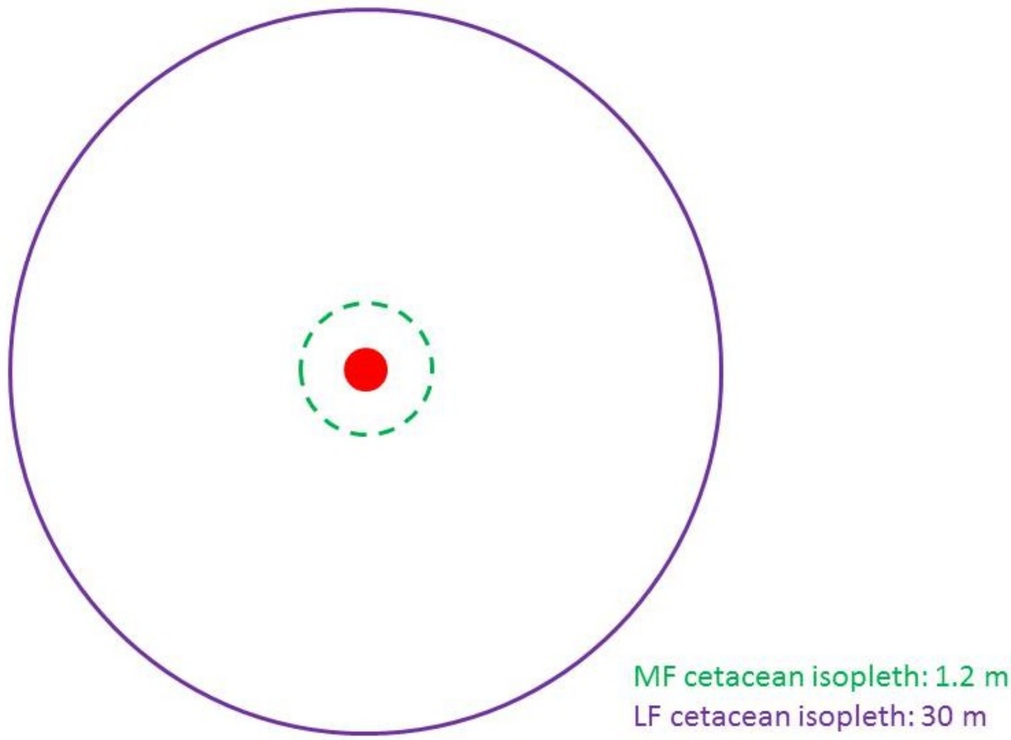


Figure D2: Simple example illustrating concept of weighting factor adjustment on isopleths for LF and MF cetaceans using hypothetical 1 kHz narrowband, intermittent source represented by the red dot (RMS source level of 200 dB; 1-second ping every 2 minutes). For a non-impulsive source, the PTS onset SEL_{cum} threshold for LF cetaceans is 199 dB, while for MF cetaceans is 198 dB. Despite LF cetaceans having a higher PTS onset threshold than MF cetaceans, the isopleth associated with LF cetaceans (30 m solid purple circle) is larger than that for MF cetaceans (1.2 m dashed green circle) based on 1 kHz being within LF cetacean's most susceptible frequency range vs. outside the most susceptible frequency range for MF cetaceans (isopleths not to scale).

2.2 APPLICATION FOR BROADBAND SOUNDS

For broadband sources, the selection of the appropriate frequency for consideration associated with WFAs is more complicated. The selection of WFAs associated with broadband sources is similar to the concept used for to determine the 90% total cumulative energy window (5 to 95%) for consideration of duration associated with the RMS metric and impulsive sounds (Madsen 2005) but considered in the frequency domain, rather than the time domain. This is typically referred to as the 95% frequency contour percentile (Upper frequency below which 95% of total cumulative energy is contained; Charif et al. 2010).

NMFS recognizes the consideration of WFAs may be new for action proponents and have provided representative "default" values for various broadband sources (see associated User Spreadsheet).

2.2.1 Special Considerations for Broadband Source

Since the intent of WFAs is to broadly account for auditory weighting functions below the 95% frequency contour percentile, it is important that only frequencies on the "left side" of the weighting function be used to make adjustments (i.e., frequencies below those where the weighting function amplitude is zero[58] or below where the function is essentially flat; resulting in every frequency below the WFA always having a more negative amplitude than the chosen WFA) (Figure D3). It is inappropriate to use WFAs for frequencies on the "right side" of the weighting function (i.e., frequencies above those where the weighting function amplitude is zero). For a frequency on the "right side" of the weighting function (Table D1), any adjustment is inappropriate and WFAs cannot be used (i.e., an action proponent would be advised to not use weighting functions and evaluate its source as essentially unweighted; see "Use" frequencies in Table D1, which will result in a weighting function amplitude of 0 dB).

Table D1: Applicability of weighting factor adjustments for frequencies associated with broadband sounds

Hearing Group	Applicable Frequencies	Non-Applicable Frequencies*
Low-Frequency Cetaceans (LF)	4.8 kHz and lower	Above 4.8 kHz (Use: 1.7 kHz)
Mid-Frequency Cetaceans (MF)	43 kHz and lower	Above 43 kHz (Use: 28 kHz)
High-Frequency Cetaceans (HF)	59 kHz and lower	Above 59 kHz (Use: 42 kHz)
Phocid Pinnipeds (PW)	11 kHz and lower	Above 11 kHz (Use: 6.2 kHz)
Otariid Pinnipeds (OW)	8.5 kHz and lower	Above 8.5 kHz (Use: 4.9 kHz)
* With non-applicable frequencies, user should input the "use" frequency in the User Spreadsheet, which will result in a weighting function amplitude of 0 dB (i.e., unweighted).		

[58] A criteria of a -0.4 dB weighting function amplitude from the Technical Guidance's auditory weighting function was used to determine the demarcation between appropriate and inappropriate frequencies to use the WFAs.

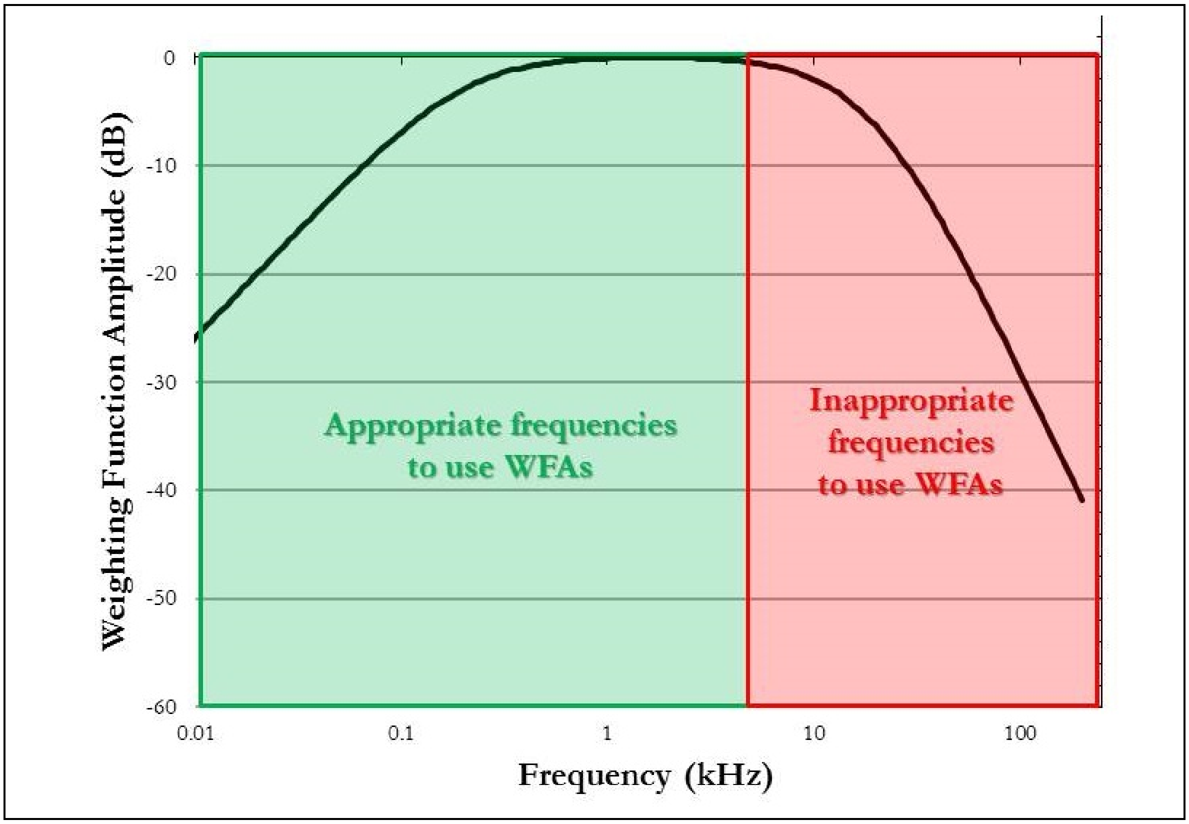


Figure D3: Example weighting function illustrating where the use of weighting function adjustments are (Green: "left side") and are not (Red: "right side") appropriate for broadband sources.

III. MODELING CUMULATIVE SOUND EXPOSURE LEVELS

To apply the PTS onset auditory acoustic thresholds expressed as the SEL_{cum} metric, accumulation time must be specified. Generally, it is predicted that most receivers will minimize their time in the closest ranges to a sound source/activity and that exposures at the closest point of approach are the primary exposures contributing to a receiver's 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., transit speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and whether species is transient or resident to the area where the activity is occurring). For all sources, NMFS recommends a baseline accumulation period of 24-h, but acknowledges that there may be specific exposure situations where this accumulation period requires an adjustment (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations[59]).

Previous NMFS acoustic thresholds only accounted for the proximity of the sound source to the receiver, but acoustic thresholds in the Technical Guidance (i.e., expressed as SEL_{cum}) now take into account the duration of exposure. NMFS recognizes that accounting for duration of exposure, although supported by the science literature, adds a new factor, as far as the application of this metric to real-world activities and that all action proponents may not have the ability to easily incorporate this additional component. NMFS 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 thresholds. All marine mammals 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.

Models that are more sophisticated 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 and can be used in the same manner as distance has been used to calculate exposures

[59] For example, where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and/or exposed to a long-duration activity with a large sound source, or there could be a continuous stationery activity nearby an area where marine mammals congregate, like a pinniped pupping beach.

above previous NMFS thresholds. NMFS proposes two alternative methods: one for mobile sources and one for stationary sources.

3.2.1 Mobile Sources[60]

3.2.1.1 Linear Equivalents Used in Appendix

In underwater acoustics, equations/derivations are typically expressed in terms of logarithmic terms (i.e., levels). These equations can be further simplified by introducing linear equivalents of the levels (i.e., factors) related by multiplication instead of by addition. For example, source level[61] (SL) is replaced by the "source factor" $10^{\mathrm{SL}/(10\ \mathrm{dB})}$ (Ainslie 2010). In this appendix, the following linear equivalents are used:

- Sound exposure (E) = $10^{\mathrm{SEL}/(10\ \mathrm{dB})}$ μPa²s
- Mean-square sound pressure ($\overline{p^2}$) = $10^{\mathrm{SPL}/(10\ \mathrm{dB})}$ μPa²
- Source factor (S) = $10^{\mathrm{SL}/(10\ \mathrm{dB})}$ μPa²m²
- Energy source factor[62] (S_E) = $10^{\mathrm{SL}_E/(10\ \mathrm{dB})}$ μPa² m²s

Both source level and energy source level (and their corresponding factors) are evaluated and reported in the direction producing the maximum SL.

3.2.1.2 "Safe Distance" Methodology

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[63] (Equation E1.; e.g., Urick 1983; ANSI 1986; Madsen 2005):

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60 The methodology for mobile sources 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 Technical Guidance.

61 For definition of SL, see Ainslie 2010. SL ≡ $10\log_{10}[p(s)^2 s^2/(1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2)]$ dB (Ainslie writes this as SL ≡ $10\log_{10} p^2 s^2$ dB re 1 μPa²s m².) For a point source, s is a small distance from the source, where distortions due to absorption, refraction, reflection, or diffraction are negligible and $p(s)$ is the RMS sound pressure at that distance. For a large (i.e., finite) source, p is the hypothetical sound pressure that would exist at distance s from a point source with the same far-field radiant intensity as the true source. For further clarification see ISO 18405 Underwater Acoustics - Terminology, entry 2.3.2.1 "source level."

62 For definition of $\mathrm{SL_E}$, see Ainslie 2010. $\mathrm{SL_E}$ ≡ $10\log_{10}[E(s)s^2/(1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s})]$ dB (Ainslie writes this as $\mathrm{SL_E}$ ≡ $10\log_{10} E(s)s^2$ dB 1 μPa² m²s). For a point source, s is a small distance from the source, where distortions due to absorption, refraction, reflection, or diffraction are negligible and $E(s)$ is the unweighted sound exposure at that distance. For a large (i.e., finite) source, E is the hypothetical sound exposure that would exist at distance s from a point source with the same duration and far-field radiant intensity as the true source. For further clarification see ISO 18405 Underwater Acoustics - Terminology, entry 2.3.2.2 "energy source level."

63 Equation D1 assumes a constant source-receiver separation distance.

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

Equation D1

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 at closest point of approach).

An alternative approach for modeling moving sources is the concept of a "safe distance" (R_0), which is defined by Sivle et al. (2014) as "the distance from the source beyond which a threshold[64] for that metric (SPL_0 or SEL_0) is not exceeded." This concept 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 the weighted SEL_{cum} PTS onset threshold in this Technical Guidance) and is further illustrated in Figure D4.

[64] The threshold considered by Sivle et al. 2014 was associated with behavioral reactions.

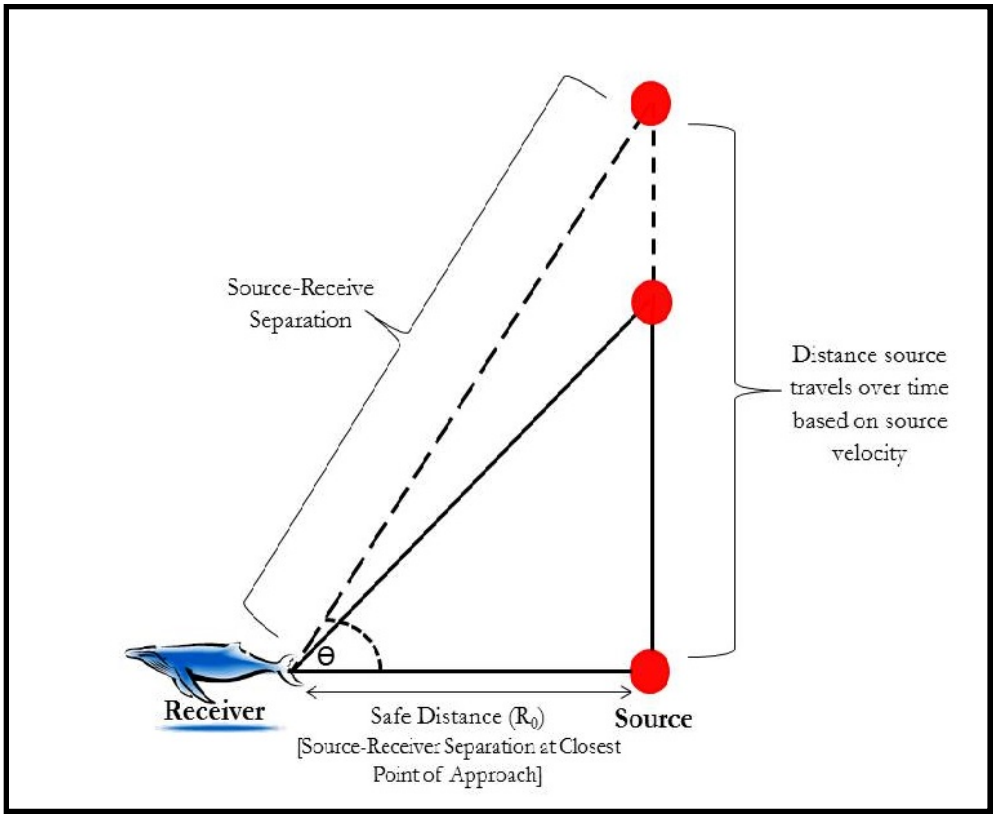

Figure D4: Illustration of the concept for mobile sources, with each red dot representing the source traveling over time. As the source travels further from the receiver, the source-receiver separation increases (i.e., hypotenuse gets longer).

This methodology accounts for several factors, including source level, duty cycle, and transit speed of the source and is independent of exposure duration (Equations D2a[65],b).

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

a

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

OR **Equations D2a,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 ($10^{SL/(10\ dB)}$ $\mu Pa^2\ m^2$)
D =duty cycle (pulse duration x repetition rate)
v= transit speed
E_0 =exposure threshold ($10^{SEL_0/(10\ dB)}$ $\mu Pa^2\ s$)
S_E = energy source factor ($10^{SL_E/(10\ dB)}$ $\mu Pa^2\ m^2\ s$)
τ = 1/repetition rate

R_0 represents the exposure isopleth calculated using NMFS' acoustic thresholds. Thus, area calculations and exposure calculations would be performed in the same manner[66] action proponents have previously used (e.g., determine area covered over a 24-h period multiplied by the density of a marine mammal species).

This approach considers four factors:

1. Source level (direct relationship: as source level increases, so does R_0; higher source level results is a greater accumulation of energy).

2. Duty cycle (direct relationship: as duty cycle increases, so does R_0; higher duty cycle results in more energy within a unit of time and leads a greater accumulation of energy).

3. Source transit speed (inverse relationship: as transit speed decreases, R_0 increases or vice versa; a faster transit speed results in less energy within a unit of time and leads to a lower accumulation of energy, while a slower transit speed will result in a greater accumulation of energy).

[66] Note: "Take" calculations are typically based on speed expressed in kilometers per hour, duration of an exposure expressed in hours (i.e., 24 hours), isopleths expressed in kilometers, and animal density expresses as animals per square kilometers. Thus, units would need to be converted to use Equations D2a,b.

4. Exposure threshold (inverse relationship: as the exposure threshold decreases, R_0 increases or vice versa; a higher exposure threshold result in needing more energy to exceed it compared to a lower threshold).

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

For this approach to be applicable to a broad range of activities, the following assumptions[67] must be made:

- Action proponents that are unable to apply full auditory weighting functions will rely on WFAs. This will create larger isopleths, for broadband sources, 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). 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.

- Minimal assumptions are made about the receivers. They 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 this methodology only examines one pass of the source relative to receiver, this method is essentially time-independent (i.e., action proponent does not need to specify how long an activity occurs within a 24-h period).

    - These assumptions are appropriate for sources that are expected to move much faster than the receiver does. Further, 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 thresholds 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 (i.e., velocity x change over time) between "pulses" for intermittent sources is small compared with R_0, and the distance between "pulses" for intermittent sources is consistent. This assumption is appropriate for intermittent sources with a

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[67] If any of these assumptions are violated and there is concern that the isopleth produced is potentially underestimated, action proponents should contact NMFS to see if any there are any appropriate adjustments that can be made (e.g., addition of a buffer, etc.). If not, the action proponent is advised to pursue other methodology capable of more accurately modeling exposure.

predictable duty cycle. If the duty cycle decreases, R_0 will become larger, while if the duty cycle increases, it will become smaller. Further, for intermittent sources, it is assumed there is no recovery in hearing threshold between pulses.

- Sound propagation is simple (i.e., approach uses spherical spreading[68]: 20 log R, with no absorption). NMFS recognizes that this might not be appropriate for all activities, especially those occurring in shallow water (i.e., sound could propagate further than predicted by this model)[69]. Thus, modifications to the R_0 predicted may be necessary in these situations.

Despite these assumptions, this 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 R_0 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 R_0 was found to be primarily driven by the exposure threshold (i.e., Technical Guidance's acoustic thresholds). Increasing duty cycle of the source or reducing speed (either source or receiver) will result in an increased R_0 (Sivle et al. 2014)

NMFS has provided a companion User Spreadsheet 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: NMFS' alternative methods apply only to acoustic thresholds in the SEL_{cum} metric. NMFS assumes action proponents will be able to perform exposure modeling using acoustic thresholds expressed using the PK metric (i.e., methodology is similar to that used with NMFS previous thresholds but with a different metric), and reminds action proponents since the Technical Guidance presents dual thresholds for impulsive sounds, they must evaluate thresholds using both metrics.

68 Assuming spherical spreading allows for Equations D2a,b to remain simplified (i.e., assuming another spreading model results in more complicated equations that are no longer user-friendly nor as easy to implement).

69 Note: Many moving sources, like seismic airguns or sonar, can be highly-directional (i.e., most of time sound source is directed to the ocean floor, with less sound propagating horizontally, compared to the vertical direction), which is not accounted for with this methodology. Additionally, many higher-frequency sounds, like sonar, are also attenuated by absorption, which is also taken into account in this model. These, among other factors, should be considered when evaluating whether spherical spreading is potentially resulting in an underestimation of exposure.

3.2.2 Stationary Sources

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 mobile source approach can be modified for stationary sources (i.e., transit speed of the source is replaced by speed of the receiver). However, NMFS 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 mobile source 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 to exceed a threshold) will remain there for the entire time of the activity.

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, action proponents should contact NMFS for possible applicable alternative methods.

NMFS has provided a companion User Spreadsheet 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: NMFS' alternative methods apply only to acoustic thresholds in the SEL_{cum} metric. NMFS assumes action proponents will be able to perform exposure modeling using acoustic thresholds expressed using the PK metric (i.e., methodology is similar to that used with NMFS previous thresholds but with a different metric) and reminds action proponents since the Technical Guidance presents dual thresholds for impulsive sounds, they must evaluate thresholds using both metrics.

APPENDIX E: GLOSSARY

95% Frequency contour percentile: Upper frequency below which 95% of total cumulative energy is contained (Charif et al. 2010).

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

Acoustic threshold: An acoustic threshold in this document identifies the level of sound, after which exceeded, NMFS anticipates 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. Audibility of sounds depends on level, frequency content, and can be reduced in the presence of other sounds (Morfey 2001)

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

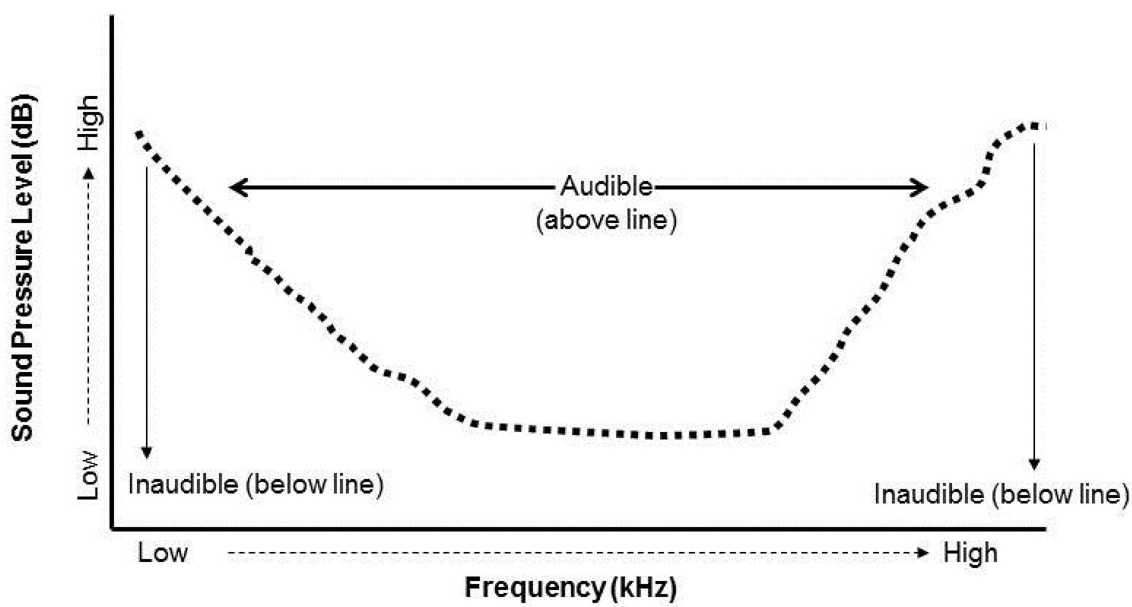

Figure E1. Example audiogram.

Auditory adaptation: Temporary decrease in hearing sensitivity occurring during the presentation of an acoustic stimulus (opposed to auditory fatigue which occurs post-stimulation) (ANSI 1995).

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

Auditory 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 2016). 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 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 or upper and lower limits of frequency band(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).

Bone conduction: Transmission of sound to the inner ear primarily by means of mechanical vibration of the cranial bones (ANSI 1995).

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).

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

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}; re: 1μPa^{2}s): 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 reference sound exposure (ANSI 1995; ANSI 2013).

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 x repetition rate). A continuous sound has a duty cycle of 1 or 100%.

Dynamic range of auditory system: Reflects the range of the auditory system from the ability to detect a sound to the amount of sound tolerated before damage occurs (i.e., the threshold of pain minus the threshold of audibility) (Yost 2007). For the purposes of this document, the intent is relating the threshold of audibility and TTS onset levels, not the threshold of pain.

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 (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.

Energy Source Level (SL_E): The time-integrated squared signal sound pressure level measured in a given radian direction, corrected for absorption, and scaled to a reference distance (1 m) (adapted from Morfey 2001).

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 latency: A curve that describe the frequency-dependent relationships between sound pressure level and reaction time and are similar in shape to equal loudness contours in humans (loudness perception can be studied under the assumption that sounds of equal loudness elicit equal reaction times; e.g., Liebold and Werner 2002).

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).

Far-field: The acoustic field sufficiently distant from a distributed source that the sound pressure decreases linearly with increasing distance (neglecting reflections, refraction, and absorption) (ANSI 2013).

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 hearing threshold at greatest hearing sensitivity (based on human and mammalian definition of 60 dB[70]).

Fundamental frequency: Frequency of the sinusoid that has the same period as the periodic quantity (Yost 2007; ANSI 2013). First harmonic of a periodic signal (Morfey 2001).

Harmonic: A sinusoidal quantity that has a frequency which is an integral multiple of the fundamental frequency of the periodic quantity to which it is related (Yost 2007; 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). 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).

[70] 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).

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

Impulsive sound: Sound sources that produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound 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 that "provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information (including 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 or exposure 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.

Marine Mammal Protection Act (MMPA): The Marine Mammal Protection Act (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.

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 sound 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).

Omnidirectional: Receiving or transmitting signals in all directions (i.e., variation with direction is designed to be as small as possible).

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

Peak sound pressure level (PK; re: 1 μPa): The greatest absolute instantaneous sound pressure within a specified time interval and frequency band (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).

Pulse duration: For impulsive sources, window that makes up 90% of total cumulative energy (5%-95%) (Madsen 2005)

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).

Received level: The level of sound measured at the receiver.

Reference pressure: See sound pressure level.

Repetition rate: Number of pulses of a repeating signal in a specific time unit, normally measured in pulses per second.

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 (RMS SPL; re: 1 μPa): The square root of the average of the square of the pressure of the sound signal over a given duration (ANSI 2005).

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

Sound Exposure Level (SEL_{cum}; re: 1μPa^{2}s): 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 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)(ANSI 2013).

Source Level (SL): Sound pressure level measured in a given radian direction, corrected for absorption, and scaled to a reference distance (Morfey 2001). For underwater sources, the sound pressure level of is measured in the far-field and scaled to a standard reference distance[71] (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).

Subharmonic: Sinusoidal quantity having a frequency that is an integral submultiple of the fundamental frequency of a periodic quantity to which it is related (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).

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[71] Standards for scaling to a reference distance will be provided in the forthcoming ISO/DIS 18405 standard.

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). It recommended that this threshold be defined as the lowest sound pressure level at which responses occur in at least 50% of ascending trials. (ANSI 2009).

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 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).

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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