

1
2
3
4
5
6
7
8

National Oceanic and Atmospheric Administration



9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals

Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts

Draft: 23 December 2013

TABLE OF CONTENTS

1		
2		
3	LIST OF TABLES	IV
4	LIST OF FIGURES.....	VI
5	ACRONYMS.....	VII
6	EXECUTIVE SUMMARY	1
7	I. INTRODUCTION	2
8	1.1 ADDRESSING UNCERTAINTY AND DATA LIMITATIONS	2
9	1.2.1 Assessment Framework.....	3
10	1.2.2 Data Standards.....	3
11	II. NOAA’S ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT AND TEMPORARY	
12	THRESHOLD SHIFTS IN MARINE MAMMALS	4
13	2.1 MARINE MAMMAL FUNCTIONAL HEARING GROUPS.....	4
14	2.2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS.....	6
15	2.2.1 Cetacean Auditory Weighting Functions	6
16	2.2.1.1 Extrapolated Auditory Weighting Function for High-Frequency Cetaceans.....	8
17	2.2.1.2 Generalized Auditory Weighting Function for Low-Frequency Cetaceans.....	9
18	2.2.2 Underwater Pinniped Auditory Weighting Functions.....	10
19	2.2.3 Implementation of Marine Mammal Auditory Weighting Functions for PTS and	
20	TTS Acoustic Threshold Levels.....	11
21	2.3 TTS AND PTS ONSET ACOUSTIC THRESHOLD LEVELS	12
22	2.3.1 Cumulative Sound Exposure Level (SEL_{cum}) Metric.....	12
23	2.3.1.1 Recommended Baseline Accumulation Period	13
24	2.3.1.2 Peak Pressure Metric	14
25	2.3.1.3 Comparison Among Metrics	15
26	2.3.1.4 Development of TTS and PTS Onset Acoustic Threshold Levels.....	15
27	III. REGULATORY CONTEXT FOR AUDITORY IMPACT ACOUSTIC THRESHOLD LEVELS FOR	
28	MARINE MAMMALS	20
29	3.1 BACKGROUND: APPLICABLE STATUTORY AND REGULATORY STANDARDS, DEFINITIONS AND	
30	PROCESSES	20
31	3.1.1 Marine Mammal Protection Act.....	20
32	3.1.2 Endangered Species Act.....	21
33	3.1.3 National Marine Sanctuaries Act.....	22
34	3.2 APPLICATION OF PERMANENT THRESHOLD SHIFT ACOUSTIC THRESHOLD LEVELS.....	22
35	3.2.1 Temporary Threshold Shift Acoustic Threshold Levels.....	23
36	IV. UPDATE OF ACOUSTIC GUIDANCE AND ACOUSTIC THRESHOLD LEVELS.....	24
37	4.1 PROCEDURE AND TIMELINE FOR UPDATING ACOUSTIC THRESHOLDS	24
38	APPENDIX A: MARINE MAMMAL AUDITORY WEIGHTING FUNCTION AMPLITUDES.....	25
39	APPENDIX B: DEVELOPMENT OF ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT	
40	AND TEMPORARY THREHSOLD SHIFT	29
41	I. DATA FOR NUMERIC ACOUSTIC THRESHOLD LEVELS BASED ON RECEIVED LEVEL	32
42	II. EXPOSURE DURATION AND FREQUENCY.....	33

1	2.1	EXPOSURE DURATION	34
2	2.1.1	<i>Recovery</i>	35
3	2.2	FREQUENCY	37
4	III.	MANAGING DATA LIMITATIONS AND UNCERTAINTY	37
5	3.1	REPRESENTATIVE SPECIES/INDIVIDUALS.....	39
6	3.2	REPRESENTATIVE SOUND SOURCES.....	39
7	IV.	DEVELOPMENT OF TTS AND PTS ONSET ACOUSTIC THRESHOLD LEVELS	41
8	4.1	TEMPORARY THRESHOLD SHIFTS: NON-IMPULSIVE SOURCES	41
9	4.1.1	<i>Mid-Frequency Cetaceans</i>	41
10	4.1.2	<i>Low-Frequency Cetaceans</i>	45
11	4.1.3	<i>High-Frequency Cetaceans</i>	45
12	4.1.4	<i>Phocid Pinnipeds (Underwater)</i>	48
13	4.1.5	<i>Otariid Pinnipeds (Underwater)</i>	50
14	4.2	TEMPORARY THRESHOLD SHIFTS: IMPULSIVE SOURCES	50
15	4.2.1	<i>Mid-Frequency and Low-Frequency Cetaceans</i>	50
16	4.2.2	<i>High-Frequency Cetaceans</i>	52
17	4.2.3	<i>Phocid Pinnipeds (Underwater)</i>	53
18	4.2.4	<i>Otariid Pinnipeds (Underwater)</i>	54
19	4.3	PERMANENT THRESHOLD SHIFTS: NON-IMPULSIVE SOURCES	54
20	4.3.1	<i>All Cetaceans</i>	55
21	4.3.2	<i>Underwater Pinnipeds</i>	57
22	4.4	PERMANENT THRESHOLD SHIFTS: IMPULSIVE SOURCES	58
23	4.4.1	<i>All Cetaceans and Underwater Pinnipeds</i>	58
24	APPENDIX C:	PEER REVIEW PROCESS	60
25	I.	PEER REVIEW PROCESS	60
26	APPENDIX D:	GLOSSARY.....	61
27	LITERATURE CITED	67	
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			
42			
43			
44			
45			
46			
47			
48			

LIST OF TABLES

1		
2		
3	Table 1:	Marine mammal functional hearing groups..... 5
4	Table 2:	Mid-frequency and high-frequency cetacean auditory weighting function
5		parameters..... 8
6	Table 3:	Low-frequency cetacean auditory weighting function parameters..... 10
7	Table 4:	Pinniped auditory weighting function parameters. 11
8	Table 5:	Currently available underwater marine mammal threshold shift peer reviewed
9		studies..... 16
10	Table 6:	a. Summary of TTS and PTS onset dual acoustic threshold levels..... 17
11		b. Other factors for considerations based on frequency and duration of exposure... 17
12	Table 7:	Alternative PTS and TTS onset dual acoustic threshold levels for applicants unable to
13		incorporate auditory weighting functions* (i.e., all acoustic threshold levels are
14		unweighted)..... 19
15	Table A1:	Low-frequency cetacean auditory weighting function amplitudes.* 25
16	Table A2:	Mid-frequency cetacean auditory weighting function amplitudes.* 26
17	Table A3:	High-frequency cetacean auditory weighting function amplitudes.* 27
18	Table A4:	Phocid auditory weighting function amplitudes.* 28
19	Table A5:	Otariid auditory weighting function amplitudes.* 28
20	Table B1:	a. Summary of TTS and PTS onset dual acoustic threshold levels..... 29
21		b. Other factors for consideration based on frequency and duration of exposure.... 29
22	Table B2:	Alternative PTS and TTS onset dual acoustic threshold levels (all acoustic threshold
23		levels are unweighted). NB stands for narrowband. 31
24	Table B3:	Currently available underwater marine mammal threshold shift studies. 33
25	Table B4:	Effect of exposure duration on TTS. 35
26	Table B5:	Existing marine mammal TTS recovery data..... 36
27	Table B6:	Effect of exposure frequency on TTS. 37
28	Table B7:	NOAA's Protocol for accounting for uncertainty in establishing TTS onset acoustic
29		threshold levels for marine mammals within a sound source category. 38
30	Table B8:	Sound sources associated with cetacean and underwater pinniped TTS studies. ... 40
31	Table B9:	TTS onset dual acoustic threshold levels for mid-frequency cetaceans exposed to
32		underwater non-impulsive sound sources. 41
33	Table B10:	TTS onset in bottlenose dolphins exposed to underwater non-impulsive sound
34		sources..... 42
35	Table B11:	TTS onset in belugas exposed to underwater non-impulsive sound sources. 42
36	Table B12:	Amount of TTS recorded in Popov et al. 2013 for belugas..... 43
37	Table B13:	Relevant studies provided in the context of exposure frequency and duration. 44
38	Table B14:	TTS onset dual acoustic threshold levels for low-frequency cetaceans exposed to
39		underwater non-impulsive sound sources. 45
40	Table B15:	TTS onset dual acoustic threshold levels for high-frequency cetaceans exposed to
41		underwater non-impulsive sound sources. 45
42	Table B16:	TTS onset in high-frequency cetaceans exposed to underwater non-impulsive sound
43		sources..... 46
44	Table B17:	Amount of TTS recorded by Popov et al. 2011a for exposures at unweighted 168 dB
45		SEL and below.* 47
46	Table B18:	Relevant studies and provided in the context of exposure frequency and duration. . 47
47	Table B19:	TTS onset dual acoustic threshold levels for underwater phocid pinnipeds exposed to
48		non-impulsive sound sources. 48
49	Table B20:	TTS onset in phocid pinnipeds exposed to underwater non-impulsive sound sources.
50		48
51	Table B21:	Relevant studies and provided in the context of exposure frequency and duration. . 49
52	Table B22:	TTS onset dual acoustic threshold levels for underwater otariid pinnipeds exposed to
53		non-impulsive sound sources. 50
54	Table B23:	Relevant studies and provided in the context of exposure frequency and duration. . 50
55	Table B24:	TTS onset dual acoustic threshold levels for mid-frequency and low-frequency
56		cetaceans exposed to underwater impulsive sound sources. 51

1	Table B25: Relevant studies and provided in the context of exposure frequency and duration..	51
2	Table B26: TTS onset dual acoustic threshold levels for high-frequency cetaceans exposed to	
3	underwater impulsive sound sources.....	52
4	Table B27: Relevant studies and provided in the context of exposure frequency and duration..	52
5	Table B28: TTS onset dual acoustic threshold levels for underwater phocid pinnipeds exposed to	
6	impulsive sound sources.....	53
7	Table B29: Relevant studies and provided in the context of exposure frequency and duration..	53
8	Table B30: TTS onset dual acoustic threshold levels for underwater otariid pinnipeds exposed to	
9	impulsive sound sources.....	54
10	Table B31: Relevant studies and provided in the context of exposure frequency and duration..	54
11	Table B32: PTS onset dual acoustic threshold levels for cetaceans exposed to underwater non-	
12	impulsive sound sources.....	55
13	Table B33: PTS onset dual acoustic threshold levels for underwater pinnipeds exposed to non-	
14	impulsive sound sources.....	57
15	Table B34: PTS onset dual acoustic threshold levels for cetaceans and pinnipeds exposed to	
16	underwater impulsive sound sources.....	58
17	Table C1: Peer review panel.	60
18		
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31		
32		
33		
34		
35		
36		
37		
38		
39		
40		
41		
42		
43		
44		
45		
46		
47		
48		
49		
50		
51		
52		

LIST OF FIGURES

1
2
3
4
5
6
7
8
9
10

Figure 1: Mid-frequency (gray line) and high-frequency (red line) cetacean merged auditory weighting functions. Complete EQL (dashed line) and M-weighting (dotted line) components of merged mid-frequency curve are illustrated..... 7

Figure 2: Low-frequency cetacean auditory weighting function..... 9

Figure 3: Underwater pinniped auditory weighting functions. 11

Figure D1. Audiogram..... 61

ACRONYMS

1					
2					
3	dB	Decibel	30	NB	Narrowband
4	dB _{peak}	Peak sound pressure level	31	NMFS	National Marine Fisheries
5	dB _{p-p}	Peak-to-peak sound	32		Service
6		pressure level	33	NMSA	National Marine Sanctuaries
7	dB _{rms}	Root mean square sound	34		Act
8		pressure level	35	NOAA	National Oceanic and
9	DOD	Department of Defense	36		Atmospheric Administration
10	EEH	Equal Energy Hypothesis	37	NOS	National Ocean Service
11	EQL	Equal Loudness	38	NS2	National Standard 2
12	ESA	Endangered Species Act	39	OMB	Office of Management and
13	HF	High-frequency	40		Budget
14	HISA	Highly Influential Scientific	41	PTS	Permanent Threshold Shift
15		Assessment	42	RL	Received Level
16	Hz	Hertz	43	RMS	Root Mean Square
17	in	Inch	44	s	Seconds
18	IQG	Information Quality	45	SEL	Sound Exposure Level
19		Guidelines	46	SEL _{cum}	Cumulative Sound Exposure
20	kHz	Kilohertz	47		Level
21	LF	Low-frequency	48	SPAWAR	The Space and Naval
22	MF	Mid-frequency	49		Warfare Systems Command
23	min	Minutes	50	SPL	Sound Pressure Level
24	MMPA	Marine Mammal Protection	51	TS	Threshold Shift
25		Act	52	TTS	Temporary Threshold Shift
26	MSA	Magnuson-Stevens Fishery	53	μPa	Micropascal
27		Conservation and	54	μPa ² -s	Micropascal squared second
28		Management Act	55	W(f)	Weighting function
29	msec	Millisecond			
56					

EXECUTIVE SUMMARY

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

NOAA has compiled, interpreted, and synthesized the best available science to produce updated acoustic threshold levels for the onset of both temporary (TTS) and permanent hearing threshold shifts (PTS). These thresholds replace those currently in use by NOAA. Updates include a protocol for estimating PTS and TTS onset levels for impulsive (e.g., airguns, impact pile drivers) and non-impulsive (e.g., sonar, vibratory pile drivers) sound sources, the formation of marine mammal functional hearing groups (low-, mid-, and high-frequency cetaceans, and otariid and phocid pinnipeds), and the incorporation of marine mammal auditory weighting functions into the calculation of thresholds. These acoustic threshold levels are presented using the dual metrics of cumulative sound exposure level and peak sound pressure level. This document addresses how to combine multiple datasets, as well as how to determine appropriate surrogates when data are not available. While the updated acoustic thresholds are more complex than those previously used by NOAA, they accurately 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 directly compare the updated thresholds presented in this document with the thresholds previously used by NOAA.

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

This acoustic guidance is classified as a Highly Influential Scientific Assessment by the Office of Management and Budget. As such, independent peer review is required prior to broad public dissemination by the Federal Government. Details of the peer review can be found within this document, and at the following website: <http://www.nmfs.noaa.gov/pr/acoustics/>.

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 provides an introduction to the document and a description of how NOAA addressed uncertainty and data limitations in the development of this guidance. NOAA's updated acoustic threshold levels for onset of PTS and TTS for marine mammals exposed to underwater sound are presented in Section II. Section III describes how acoustic threshold levels are interpreted under NOAA's statutes. NOAA's plan for periodically updating acoustic threshold levels is presented in Section IV. More details on the marine mammal auditory weighting functions, the development of acoustic threshold levels, the peer review process, and a glossary of acoustic terms can be found in the appendices.

1 **National Oceanic and Atmospheric Administration**
2 **DRAFT Guidance for Assessing the Effects**
3 **of Anthropogenic Sound on Marine Mammals**
4

5 **Acoustic Threshold Levels for Onset of Permanent and**
6 **Temporary Threshold Shifts**
7

8
9 **I. INTRODUCTION**
10

11 This document provides guidance for assessing the effects of anthropogenic sound on marine
12 mammal species under the jurisdiction of the National Marine Fisheries Service (NMFS) and the
13 National Ocean Service (NOS) (hereafter referred to collectively as the National Oceanic and
14 Atmospheric Administration (NOAA)). Specifically, it identifies the received levels, or thresholds,
15 above which individual marine mammals are predicted to experience changes in their hearing
16 sensitivity (either temporary or permanent) for all underwater anthropogenic sound sources. This
17 guidance is intended to be used by NOAA analysts and managers and other relevant user groups
18 and stakeholders, including other federal agencies, when seeking to determine whether and how
19 their activities are expected to result in particular types of impacts to marine mammals via
20 acoustic exposure. This document outlines NOAA's updated acoustic threshold levels and
21 describes in detail how the thresholds were developed and how they will be revised and updated
22 in the future.
23

24 The updated acoustic threshold levels presented do not represent the entirety of an impact
25 assessment, but rather serve as one tool (in addition to behavioral impact thresholds, auditory
26 masking assessments, evaluations to help understand the ultimate effects of any particular type
27 of impact on an individual's fitness, population assessments, etc.), to help evaluate the effects of
28 a proposed action on marine mammals and make findings required by our various statutes. This
29 document does not provide acoustic threshold levels for non-auditory injury (i.e., lung injury or
30 gastrointestinal tract injury), or exposure to airborne sounds for pinnipeds, and does not address
31 mitigation measures that may be associated with particular activities.
32

33 This document had been classified as a Highly Influential Scientific Assessments (HISA)¹ by the
34 Office of Management and Budget (OMB); as such, independent peer review was required before
35 it could be disseminated more broadly by the Federal Government. NOAA also sought informal
36 input from key federal agencies regarding various aspects of this document.
37

38
39 **1.1 Addressing Uncertainty and Data Limitations**
40

41 NOAA acknowledges the inherent data limitations that occur in many instances when assessing
42 acoustic effects on marine mammals. Data limitations, which make it difficult to account for
43 uncertainty and variability, are not unique to assessing the effects of anthropogenic sound on
44 marine mammals and are commonly encountered by resource managers (Ludwig et al. 1993;
45 Francis and Shotton 1997; Harwood and Stokes 2003; Punt and Donovan 2007). Southall et al.
46 (2007) acknowledged the inherent data limitations when assessing acoustic effects on marine
47 mammals (e.g., data available from a limited number of species, a limited number of individuals
48 within a species, and/or limited number of sound sources). They applied certain extrapolation
49 procedures to estimate effects that had not been directly measured but that could be reasonably
50 approximated using existing information and reasoned logic. NOAA acknowledges these

¹ 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).

1 limitations, as well as the need for using the best available science to make decisions in cases
2 where data are lacking. Where NOAA has faced such uncertainty and variability in the
3 development of its proposed acoustic threshold levels, we have articulated our extrapolation
4 methodology. As such, the contents of this document include the development of an assessment
5 framework, including data standards and extrapolation procedures, used to date, to address data
6 limitations.

9 **1.2.1 Assessment Framework**

10 NOAA's approach applies a set of assumptions to develop a framework that addresses
11 uncertainty in predicting potential effects of sound on individual marine mammals. One of these
12 assumptions includes the use of "representative" or surrogate individuals/species for establishing
13 TTS and PTS onset acoustic threshold levels for species where little to no data exist. The use of
14 representative individuals/species is done as a matter of practicality (i.e., it is unlikely that
15 adequate data will exist for the 125² marine mammal species found worldwide or that we will be
16 able to account for all sources of variability at an individual level), but is also scientifically based
17 (i.e., taxonomy, functional hearing group). As new data become available for more species, this
18 approach will be reevaluated.

19
20
21 These procedures and assumptions (further described in Appendix B), along with our stipulated
22 data standards (see Appendix B, Section III), are intended to ensure that data are assessed and
23 such procedures are subsequently modified in a consistent manner. NOAA recognizes that
24 additional applicable data may become available to allow us to better address many of these
25 issues. As these new data become available, NOAA has an approach for updating our acoustic
26 threshold levels (see Section IV).

29 **1.2.2 Data Standards**

30
31 In assessing potential acoustic effects on marine mammals, as with any such issue facing the
32 agency, standards for determining applicable data need to be articulated. Specifically, NOAA has
33 Information Quality Guidelines³ (IQG) for "ensuring and maximizing the quality, objectivity, utility,
34 and integrity of information disseminated by the agency" (with each of these terms defined within
35 the IQG). Furthermore, the IQG stipulate that "To the degree that the agency action is based on
36 science, NOAA will use (a) the best available science and supporting studies (including peer-
37 reviewed science and supporting studies when available), conducted in accordance with sound
38 and objective scientific practices, and (b) data collected by accepted methods or best available
39 methods."

40
41 The National Research Council (NRC 2004) provided basic guidelines on National Standard 2
42 (NS2)⁴ under the Magnuson-Stevens Fishery Conservation and Management Act, section 301,
43 which stated "Conservation and management measures shall be based upon the best scientific
44 information available." They recommended that data underlying the decision-making and/or
45 policy-setting process be: 1) relevant, 2) inclusive, 3) objective, 4) transparent and open, 5)
46 timely, 6) verified and validated, and 7) peer reviewed⁵. Although NRC's guidelines (NRC 2004)

² Current number of marine mammal species worldwide recognized by NMFS Office of Protected Resources (see <http://www.nmfs.noaa.gov/pr/species/>)

³ http://www.st.nmfs.noaa.gov/science-quality-assurance/national-standards/ns2_revisions

⁴ NOAA is currently proposing revisions to NS2 to provide guidance on the use of best scientific information available (NOAA 2013).

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

1 were not written specifically for marine mammals and this particular issue, they do provide a
2 means of articulating minimum data standards. NOAA is taking this into account in assessing
3 acoustic effects on marine mammals. Use of the NRC Guidelines does not preclude development
4 of acoustic-specific data standards in the future.
5
6

7 **II. NOAA'S ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT** 8 **AND TEMPORARY THRESHOLD SHIFTS IN MARINE MAMMALS** 9

10 This document advances NOAA's assessment ability based upon the best available science. As
11 described in detail in this section, this includes both quantitative and qualitative approaches
12 based on the best available science. Quantitative assessment consists of two parts: 1) an
13 acoustic threshold level and 2) an associated weighting function (when appropriate) based upon
14 measured and approximated marine mammal equal loudness contours. Additionally, qualitative
15 considerations that illustrate general trends associated with noise-induced hearing loss are
16 provided and may be useful within a larger assessment, even though they cannot be applied
17 quantitatively.
18

19 This document provides acoustic threshold levels for the onset of PTS and TTS based on
20 characteristics defined at the source and not the receiver. No direct data on marine mammal PTS
21 exist; PTS onset thresholds have been extrapolated from marine mammal TTS data. PTS and
22 TTS onset acoustic threshold levels, for all sound sources, are divided into two broad categories:
23 1) impulsive and 2) non-impulsive. Acoustic threshold levels are also presented as dual acoustic
24 threshold levels using cumulative sound exposure level (SEL_{cum}) and peak pressure (dB_{peak})
25 metrics. As dual metrics, NOAA considers onset of PTS or TTS to have occurred when either one
26 of the two metrics is exceeded. Additionally, to account for the fact that different species groups
27 use and hear sound differently, acoustic threshold levels are sub-divided into five broad functional
28 hearing groups (i.e., low-, mid-, and high-frequency cetaceans and phocid and otariid pinnipeds).
29 Where appropriate, the PTS and TTS onset acoustic threshold levels include marine mammal
30 auditory weighting functions.
31
32

33 **2.1 Marine Mammal Functional Hearing Groups** 34

35 Current data (via direct measurements [behavioral and electrophysiological]) and predictions
36 (based on inner ear morphology, behavior, vocalizations, or taxonomy) indicate that not all marine
37 mammal individuals/species have equal hearing capabilities, in terms of absolute hearing
38 sensitivity and the frequency band of hearing (Richardson et al. 1995; Wartzok and Ketten 1999;
39 Southall et al. 2007; Au and Hastings 2008). Hearing has been directly measured in a multitude
40 of odontocete and pinniped species⁶ (see review in Southall et al. 2007). Direct measurements of
41 mysticete hearing are lacking (e.g., there was an unsuccessful attempt to directly measure
42 hearing in a stranded gray whale calf by Ridgway and Carder 2001). Thus, hearing predictions for
43 mysticetes are based on other methods (e.g., anatomical studies: Houser et al. 2001; Parks et al.
44 2007; vocalizations⁷: see reviews in Richardson et al. 1995; Wartzok and Ketten 1999; Au and
45 Hastings 2008; taxonomy and behavioral responses to sound: Dahlheim and Ljungblad 1990; see
46 review in Reichmuth 2007).
47

48 To more accurately reflect marine mammal hearing capabilities, Southall et al. (2007)
49 recommended that marine mammals be divided into functional hearing groups based on

⁶ Both in air and underwater for pinniped species.

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

1 measured or estimated functional hearing ranges. NOAA modified the functional hearing groups
 2 proposed by Southall et al. (2007)⁸ as follows (Table 1):
 3

- 4 • Extension of upper end of low-frequency cetacean hearing range: NOAA extended
 5 slightly the estimated upper end of the hearing range for low-frequency cetaceans, from
 6 22 to 30 kHz, based on data from Watkins et al. (1986) for numerous mysticete species
 7 (variety of mysticete species responding to sounds up to 28 kHz), Au et al. (2006) for
 8 humpback whales (songs having harmonics that extend beyond 24 kHz), Lucifredi and
 9 Stein (2007) for gray whales (reported potentially responding to sounds beyond 22 kHz),
 10 and an unpublished report (Ketten and Mountain 2009) and data (Tubelli et al. 2012) for
 11 minke whales (predicted hearing range of up to 30 kHz based on inner ear anatomy).
 12 These new data indicate that some mysticetes can hear above 22 kHz. As more data
 13 become available, these estimated hearing ranges may require future modification.
 14
 15

16 **Table 1: Marine mammal functional hearing groups.**
 17

Functional Hearing Group	Functional Hearing Range*
Low-frequency (LF) cetaceans ⁺ (baleen whales)	7 Hz to 30 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, <i>Kogia</i> , river dolphins, cephalorhynchid, <i>Lagenorhynchus cruciger</i> and <i>L. australis</i>)	200 Hz to 180 kHz
Phocid pinnipeds (true seals)	75 Hz to 100 kHz
Otariid pinnipeds (sea lions and fur seals)	100 Hz to 40 kHz

* Represents frequency band of hearing for entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad.
 + Estimated hearing range for low-frequency cetaceans is based on behavioral studies, recorded vocalizations, and inner ear morphology measurements. No direct measurements of hearing ability have been successfully completed.

- 18
 19
 20 • Division of pinnipeds into phocids and otariids: NOAA subdivided pinnipeds into their two
 21 families: Phocidae and Otariidae. Based on a review of the literature, phocid species
 22 have consistently demonstrated an extended frequency range of hearing compared to
 23 otariids, especially in the higher frequency range (Hemilä et al. 2006; Kastelein et al.
 24 2009; Reichmuth et al. 2013). This is believed to be because phocid ears are
 25 anatomically distinct from otariid ears in that phocids have larger, more dense middle ear
 26 ossicles, inflated auditory bulla, and larger portions of the inner ear (i.e., tympanic
 27 membrane, oval window, and round window), which make them more adapted for
 28 underwater hearing (Terhune and Ronald 1975; Kastak and Schusterman 1998; Hemilä
 29 et al. 2006; Mulsow et al. 2011; Reichmuth et al. 2013).
 30
 31 • Addition of hourglass (*Lagenorhynchus cruciger*) and Peale's (*L. australis*) dolphins to
 32 high-frequency functional hearing group: Recent echolocation data (Kyhn et al. 2009;
 33 Kyhn et al. 2010; Tougaard et al. 2010) indicate that these two species produce sounds
 34 (i.e., higher mean peak frequency) similar to other narrow band high-frequency
 35 cetaceans, such as porpoises, *Kogia*, and *Cephalorhynchus*, and are distinctly different
 36 from other *Lagenorhynchus* species. Genetic data also suggest these two species are
 37 more closely related to other *Cephalorhynchus* species (May-Collado and Agnarsson
 38 2006). Thus, NOAA has decided to move these two species from the mid-frequency

⁸ NOAA considered separating sperm whales from other MF cetaceans, but there are currently not enough data to stipulate exactly how this should be done.

1 functional hearing group (MF cetaceans) to the high-frequency functional hearing group
2 (HF cetaceans).
3
4

5 **2.2 Marine Mammal Auditory Weighting Functions**

6

7 The ability to hear sounds varies across a species functional hearing range. Most mammal
8 audiograms have a typical “U-shape”, with frequencies at the bottom of the “U” being those to
9 which the animal is more sensitive, in terms of hearing (i.e. the animal’s best hearing range)⁹. To
10 reflect this higher sensitivity at particular frequencies, sounds are often weighted (e.g., A-
11 weighting for humans where frequencies below 1 kHz and above 6 kHz are deemphasized; e.g.,
12 Fletcher and Munson 1933; Suzuki and Takeshima 2004). There are other types of weightings for
13 humans, as well (e.g., B, C, D) that deemphasize different frequencies to different extremes.
14

15 Auditory weighting functions have recently been proposed for marine mammals, specifically
16 associated with PTS and TTS acoustic threshold levels expressed in the cumulative sound
17 exposure level metric (SEL_{cum})¹⁰, which take into account what is known about marine mammal
18 hearing (Southall et al. 2007; Finneran and Jenkins 2012). Finneran and Jenkins (2012)¹¹
19 developed auditory weighting functions specifically for cetaceans, including extrapolation
20 procedures when no data were available. These auditory weighting functions reflect frequencies
21 within which functional hearing groups are most sensitive to sound in terms of hearing and
22 vulnerability to noise-induced threshold shifts. Compared to human auditory weighting functions,
23 the proposed weighting functions for cetaceans (“M-weighting”) are a hybrid of A-weighting
24 functions for frequencies that marine mammals are expected to be more susceptible to threshold
25 shifts from sound exposure (i.e., where we have data: Finneran and Schlundt 2009; Finneran and
26 Schlundt 2010; Finneran and Schlundt 2011; Finneran and Schlundt 2013) and broad C-
27 weighting functions for frequencies where fewer data are available (i.e., more uncertainty:
28 Southall et al. 2007).
29
30

31 **2.2.1 Cetacean Auditory Weighting Functions**

32

33 Cetacean auditory weighting functions merge the marine mammal or “M-weighting” functions
34 proposed in Southall et al. (2007) with a more recently derived Equal Loudness (EQL) weighting
35 function based on bottlenose dolphin (MF cetacean)¹² equal loudness measurements (Finneran
36 and Schlundt 2011) and frequency-specific TTS data (Finneran and Schlundt 2010; Finneran and
37 Schlundt 2009; Finneran and Schlundt 2013) (Figure 1). The modification of the original Southall
38 et al. (2007) auditory weighting functions reflects the incorporation of more recent data on
39 frequencies with a relatively increased susceptibility to noise-induced threshold shifts. This hybrid
40 function was then used to extrapolate similar weighting functions for HF cetaceans, where no
41 data currently exist (Finneran and Jenkins 2012). A similar extrapolation was proposed for LF

⁹ Auditory weighting functions best reflect an animal’s ability to hear a sound. It may not necessarily reflect how an animal will perceive that sound and behaviorally react to that sound.

¹⁰ Auditory weighting functions are not to be applied to PTS or TTS onset acoustic threshold levels expressed as the peak pressure metric.

¹¹ Finneran and Jenkins (2012) specifically addressed Navy sonar and explosive usage with their updated criteria and weighting functions. Other sound sources, like pile driving and seismic relied on NMFS’ generic criteria (i.e., 180/190 dB for auditory injury for cetaceans and pinnipeds for impulse and continuous sources) and does not incorporate auditory weighting functions. This guidance document updates the auditory injury acoustic threshold levels for all sounds sources (i.e., replaces the generic 180/190 dB level) and includes the incorporation of auditory weighting functions.

¹² Since data for no other marine mammal species are available, the assumption is that bottlenose dolphins are an appropriate surrogate for the entire MF cetacean group and that a similar trend would be predicted for all other echolocating cetaceans.

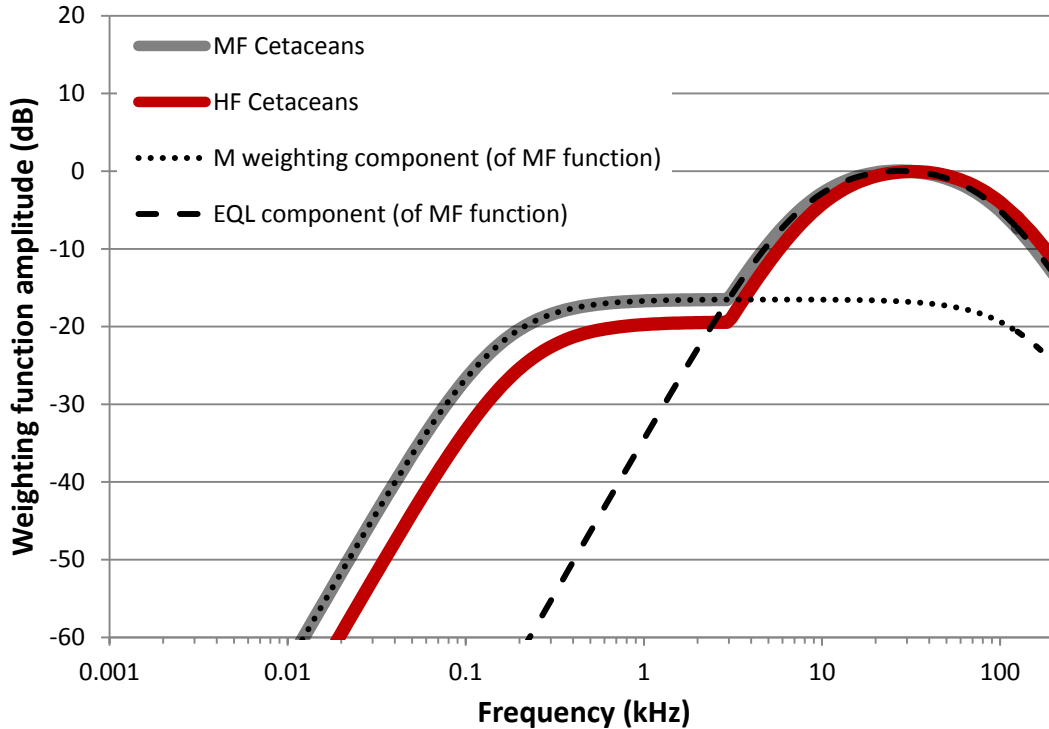
1 cetaceans by Finneran and Jenkins, but NOAA derived LF cetacean auditory weighting function
2 input parameters in a different manner (See Section 2.2.1.2).

3
4 To derive the merged cetacean weighting function, both the M-weighting and EQL curves are
5 plotted, with the maximum weighting function amplitude at each frequency taken to define the
6 merged curve. Each of the two component curves can be calculated with the following equation
7 (Southall et al. 2007; Finneran and Jenkins 2012):

$$W(f) = K + 20 \log_{10} \left[\frac{b^2 f^2}{(a^2 + f^2)(b^2 + f^2)} \right]$$

8
9
10 In this equation, f is frequency (Hz), a and b are the parameters that define the appropriate “roll
11 off” frequency limits to each component portion of the curve, and K is a constant used to
12 normalize the equation to a particular frequency (Finneran and Jenkins 2012). For the M-
13 weighting curve, a and b are related to the lower and upper hearing limits (Hz) of a functional
14 hearing group. For the EQL curve, lower (a) and upper frequency (b) cut-offs for MF cetaceans
15 were derived from the 90 dB equal loudness contour obtained from a bottlenose dolphin
16 (Finneran and Schlundt 2011), which is assumed to be an appropriate surrogate species for the
17 entire MF cetacean functional hearing group. The parameters for each of these functions, as
18 proposed in Finneran and Jenkins (2012), are listed in Table 2.

19
20
21 This equation produces a weighting function amplitude (in dB) at each frequency for each of the
22 two component functions. The highest weighting function amplitude at each frequency then
23 defines the merged curve, with M-weighting generally determining the lower frequencies, while
24 the EQL curve determines higher frequencies (Figure 1).



27
28 **Figure 1:** Mid-frequency (gray line) and high-frequency (red line) cetacean merged
29 auditory weighting functions. Complete EQL (dashed line) and M-weighting
30 (dotted line) components of merged mid-frequency curve are illustrated.

Table 2: Mid-frequency and high-frequency cetacean auditory weighting function parameters.

Functional Hearing Group	M-Weighting			EQL Weighting		
	K	a (Hz)	b (Hz)	K	a (Hz)	b (Hz)
Mid-frequency (MF) cetacean	-16.5	150	160,000	1.4	7829	95,520
High-frequency (HF) cetacean	-19.4	200	180,000	1.4	9480	108,820

2.2.1.1 Extrapolated Auditory Weighting Function for High-Frequency Cetaceans

Because equal loudness data are not available and only limited TTS data exist for most cetacean functional hearing groups, auditory weighting functions were estimated using bottlenose dolphin data (Finneran and Jenkins 2012). NOAA considered this extrapolation appropriate for HF cetaceans, since they use and hear sound in a similar manner to MF cetaceans (e.g., both MF and HF cetaceans echolocate).

Ketten (2000) indicated that cetaceans with Type II cochlea (i.e., typically those classified as MF cetaceans) echolocate with peak frequencies below 80 kHz, while cetaceans with Type I cochlea (i.e., typically those already classified as HF cetaceans) echolocate with peak frequencies above 100 kHz. Thus, based on auditory anatomy and vocalizations, it would seem that HF cetaceans would be more sensitive to higher frequencies compared to MF cetaceans.

However, the auditory weighting functions presented in this document are used specifically in conjunction with proposed PTS and TTS onset acoustic threshold levels and are intended to reflect not only the frequencies that functional hearing groups hear best, but also their susceptibility to noise-induced hearing loss. When new auditory weighting functions were proposed for MF cetaceans incorporating recent bottlenose dolphin data on equal loudness measurements (Finneran and Schlundt 2011) and frequency-specific temporary threshold shifts (Finneran and Schlundt 2009; Finneran and Schlundt 2010; Finneran and Schlundt 2013), HF cetacean TTS studies were examined to see if similar trends existed (there are no data on equal loudness for any HF cetacean). The only TTS study for HF cetaceans available examined hearing loss in higher frequency ranges in Yangtze finless porpoise (Popov et al. 2011a). This study exposed two individuals to half-octave band noise (-1 to +0.5 octaves) relative to 32, 45, 64, and 128 kHz. In this paper, Popov et al. (2011a) also presented baseline hearing data of the two individuals used in the study, which indicated greatest auditory sensitivity between 45 to 139 kHz. However, the general finding from this study was that the lower frequency ranges (where auditory sensitivity was reduced) were more impacted by noise than the higher frequency ranges (where auditory sensitivity was greatest).

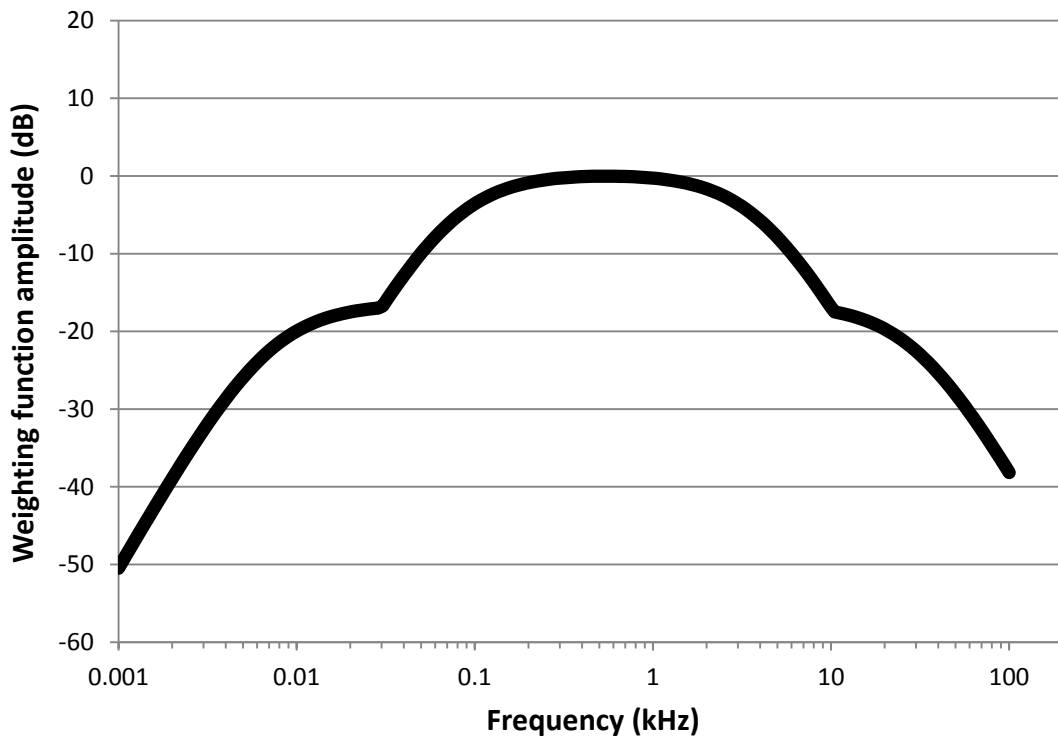
Finneran and Schlundt (2013) also indicated that TTS susceptibility might not necessarily directly reflect hearing sensitivity. Their research, along with Popov et al. (2013), found that MF cetaceans (i.e., bottlenose dolphin and belugas) have increased susceptibility to TTS at frequencies from 10 to 30 kHz. Popov et al. 2011a seems to indicate a similar finding, in terms of the TTS susceptibility range, for HF cetaceans (i.e., Yangtze finless porpoise). Thus, based on these data, there does not seem to be justification to modify the HF cetacean weighting function (i.e., EQL weighting parameters) proposed by Finneran and Jenkins (2012).

Upper and lower cut-offs for HF cetaceans were derived for the EQL weighting function by extrapolating from those values calculated for MR cetaceans. The approach used was based on octave spacing (log base 2; ANSI 1994), which reflects what is known about the organization of

1 the ear and perception of frequency (i.e., base-2 logarithmic perception; Yost 2007; Ketten 2000).
2 The resulting extrapolated parameters are presented in Table 2.

3 4 5 **2.2.1.2 Generalized Auditory Weighting Function for Low-Frequency Cetaceans**

6
7 Finneran and Jenkins (2012) also proposed an updated auditory weighting function for LF
8 cetaceans based on similar methodology used to create auditory weighting functions for HF
9 cetaceans. However, their LF auditory weighting function predicted that the EQL portion of the
10 function (which while flatter, is generally reflective of the region of best auditory sensitivity) would
11 indicate highest susceptibility to noise-induced threshold shifts between approximately 700 Hz
12 and 12 kHz. As the EQL curve is generally flatter than an inverse audiogram would be expected
13 to be, this would suggest the region of best hearing sensitivity in LF cetaceans would be in an
14 even narrower range between these two frequencies. Based on what is known about the
15 predominant vocal range of LF cetaceans, as well as hypothesized sensitivity to lower frequency
16 sounds, the Finneran and Jenkins (2012) auditory weighting function was deemed not to reflect
17 what is currently known about LF cetaceans' potential auditory capabilities. Thus, NOAA decided
18 to develop an alternative LF cetacean auditory weighting function (Figure 2).
19



20
21
22 **Figure 2: Low-frequency cetacean auditory weighting function.**

23
24
25 Developing an auditory weighting function for LF cetaceans is difficult because of a general lack
26 of empirical data on what frequencies these marine mammals hear. However, LF cetaceans are
27 predicted to have good sensitivity from 20 Hz to 2 kHz (Ketten 1998), with some species like
28 humpback (Houser et al. 2001) and minke whales (Tubelli et al. 2012) predicted to have an
29 expanded best hearing range (i.e., up to 6 to 7.5 kHz) base upon inner ear anatomy.

30
31 Vocalization range was also considered as an appropriate predictor of best sensitivity for LF
32 cetaceans. Ketten (1998) indicated "Most animals have vocalizations that are tightly linked to their

1 peak hearing sensitivities in order to maximize intra-specific communication, but they also have
 2 hearing beyond that peak range that is related to the detection of acoustic cues from predators,
 3 prey, or other significant environmental cues.” For LF cetaceans, vocal frequency with maximum
 4 energy typically is below 4 kHz and primarily below 1 kHz for most species (Ketten 1998).
 5

6 Both MF and HF weighting functions are comprised of two component curves, and EQL and M-
 7 weighting curves. These same two component curves were used to develop the LF cetacean
 8 weighting function. Auditory weighting function parameters (*a* and *b* frequency limits) were
 9 modified in order to better reflect what is reasonably assumed about potential auditory capabilities
 10 of LF cetaceans (Table 3). This modification was chosen instead of extrapolating the *a* and *b*
 11 parameters of the EQL portion of the curve by assuming the same relationship to the overall
 12 functional hearing limits as exists in MF cetaceans (as was done with HF cetaceans, and as
 13 proposed by Finneran and Jenkins (2012) for LF cetaceans leading to a likely displaced region of
 14 best sensitivity). This included setting the *a* and *b* parameters encompassing the EQL portion of
 15 the curve at 75 Hz and 4 kHz respectively¹³, as well as extending the upper frequency functional
 16 hearing limit from 22 kHz to 30 kHz for the M-weighted portion of the curve.
 17
 18

19 **Table 3: Low-frequency cetacean auditory weighting function parameters.**
 20

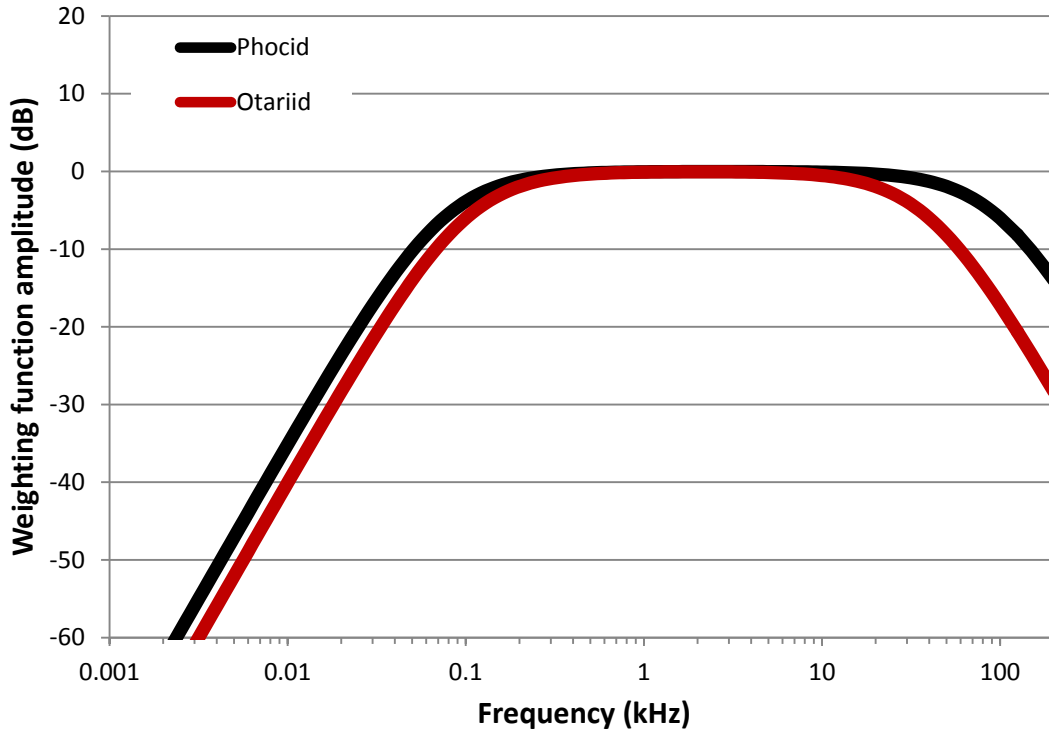
Functional Hearing Group	M Weighting			EQL Weighting		
	K	<i>a</i> (Hz)	<i>b</i> (Hz)	K	<i>a</i> (Hz)	<i>b</i> (Hz)
Low-frequency (LF) cetaceans	-16.5	7	30,000	0.3	75	4,000

21
 22
 23 **2.2.2 Underwater Pinniped Auditory Weighting Functions**
 24

25 Underwater pinniped auditory weighting functions are derived solely from the M-weighting
 26 function (i.e., their weighting functions do not contain the EQL curve component; Figure 3),
 27 because EQL measurements have not been obtained for any pinniped species, and data are
 28 therefore insufficient to incorporate an analogous region of higher susceptibility to noise induced
 29 threshold shifts. While future EQL measurements in pinnipeds may provide the data necessary to
 30 generate an EQL portion of the curve, currently, none of the available TTS datasets indicate that
 31 pinnipeds are more susceptible to noise-induced threshold shifts within a certain portion of their
 32 auditory range¹⁴. NOAA has therefore adopted the methodology for deriving auditory weighting
 33 functions for pinnipeds presented in Southall et al. (2007) and Finneran and Jenkins (2012).
 34 Because phocids have consistently demonstrated an extended frequency range of hearing
 35 compared to otariids, particularly at higher frequencies. NOAA has modified the upper functional
 36 hearing range of phocid pinnipeds by extending it from 75 to 100 kHz based on data presented in
 37 Hemilä et al. (2006) and Kastelein et al. (2009).
 38

¹³ Fin and blue whales regularly vocalize in the 20-50Hz range, which may suggest a lowering the *a* parameter. However, the evolution of hearing in typical ambient noise conditions would suggest lower sensitivity at these very low frequencies as the noise floor is increased (Clark and Ellison 2004). While this has not been accounted for in the LF cetacean curve, it suggests that these cetaceans may have evolved and increased hardiness and be less susceptible to hearing effects from these lower, typically louder, frequencies.

¹⁴ NOAA acknowledges that compared to cetaceans, there have been far fewer TTS studies completed on pinnipeds. As more data become available, NOAA will re-evaluate these pinniped auditory weighting functions.



1
2
3 **Figure 3: Underwater pinniped auditory weighting functions.**
4
5

6 The auditory weighting functions for pinnipeds are represented by the same equation as
7 cetaceans (Southall et al. 2007; Finneran and Jenkins 2012). In the case of pinniped auditory
8 weighting functions, the K constant is zero because the weighting function is essentially flat
9 through most of the auditory range (i.e., does not need to be normalized to any frequency).

10 NOAA has adopted this methodology for deriving auditory weighting functions for pinnipeds, but
11 has modified it to create separate weighting functions for phocid and otariid pinnipeds, based on
12 updated data, using the following parameters (Table 4):
13
14
15

16 **Table 4: Pinniped auditory weighting function parameters.**
17

Functional Hearing Group	Weighting		
	K	a (Hz)	b (Hz)
Phocid pinnipeds (underwater)	0	75	100,000
Otariid pinnipeds (underwater)	0	100	40,000

18
19
20 **2.2.3. Implementation of Marine Mammal Auditory Weighting Functions for PTS and TTS**
21 **Acoustic Threshold Levels**
22

23 The implementation of marine mammal auditory weighting functions emphasizes the importance
24 of making measurements and characterizing sound sources in terms of biologically important
25 frequencies (e.g., frequencies used for environmental awareness, communication or the detection
26 of predators or prey), not only the frequencies of interest or concern for the completion of the
27 sound-producing activity (i.e., context of sound source). Marine mammal auditory weighting
28 functions will be used in two aspects of an impact assessment:

- 1
- 2
- 3 1) After considering and evaluating all available data, establishing numerical acoustic
- 4 threshold levels for PTS and TTS onset (for SEL_{cum} metric threshold only; the peak
- 5 pressure metric threshold is not weighted), which is NOAA's responsibility; and
- 6
- 7 2) Determining PTS and TTS onset isopleths (i.e., modeling of the area impacted
- 8 around a source) associated with an activity, which is typically completed by an
- 9 applicant/federal agency.

10 If the frequencies produced by a sound source are outside the range of a functional hearing
11 group's best hearing sensitivity (where the weighting function amplitude is 0), sounds must be
12 louder in order to produce a similar to noise-induced hearing loss (i.e., TTS or PTS onset). The
13 farther a sound source's frequency is away from the range of best sensitivity, the louder it must
14 be. Because auditory weighting functions take a functional hearing group's differing sensitivity to
15 frequencies into account, the implementation of these functions typically results in smaller
16 isopleths at frequencies where the group is less sensitive. These marine mammal auditory
17 weighting functions should be used in conjunction with corresponding PTS and TTS onset
18 acoustic threshold levels, derived using auditory weighting functions. If the use of auditory
19 weighting functions is not possible, NOAA has provided alternative, non-weighted PTS and TTS
20 onset acoustic threshold levels to be used (Table 7).

21

22

23 **2.3 TTS and PTS Onset Acoustic Threshold Levels**

24

25 This section provides numeric acoustic threshold levels for the onset of TTS and PTS (Tables 6a,
26 weighted and 7, non-weighted). Dual metrics of SEL_{cum} and peak sound pressure level have been
27 recommended as most appropriate for establishing TTS and PTS onset acoustic threshold levels
28 for marine mammals (Southall et al. 2007).

29

30 Based on data from cetacean TTS studies (see Southall et al. 2007 for a review), a threshold shift
31 of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-
32 to-session variation in a subject's normal hearing ability (Schlundt et al. 2000; Finneran et al.
33 2000; Finneran et al. 2002). Available data from humans and other terrestrial mammals indicate
34 that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward 1960;
35 Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

36

37 The acoustic threshold levels presented in Table 6a replace previously issued NOAA acoustic
38 threshold levels and are similar to those proposed elsewhere (Finneran and Jenkins 2012).
39 However, the acoustic threshold levels described below also take into account new TTS data
40 available, and follow a protocol developed by NOAA for combining multiple datasets. In addition
41 to providing numeric acoustic threshold levels, NOAA has provided qualitative factors (Table 6b)
42 that can be considered in conjunction with utilizing the numeric acoustic threshold levels. Numeric
43 levels consist of both an acoustic threshold level and weighting function for the SEL_{cum} metric
44 (weighting functions are not appropriate for peak pressure metric; see Section 2.3.2). NOAA
45 recognizes that the implementation of marine mammal weighting functions represents a new and
46 complicating factor for consideration, which may extend beyond the capabilities of some
47 applicants. Thus, NOAA has developed alternative acoustic threshold levels for those who cannot
48 apply weighting functions (Table 7). The use of these alternative acoustic threshold levels will
49 typically result in a higher number of exposures compared to those that incorporate weighting
50 functions.

51

52

53 **2.3.1 Cumulative Sound Exposure Level (SEL_{cum}) Metric**

54

55 The SEL metric takes into account both source level and duration of exposure (ANSI 1994). Often
56 this metric is used to normalize a single sound exposure to a duration of one second. NOAA

1 intends for the SEL metric to account for the *accumulated* exposure (i.e., SEL_{cum} cumulative
2 exposure over the duration of the activity¹⁵).

3
4 One assumption made when using the SEL_{cum} metric is the equal energy hypothesis (EEH),
5 where it is assumed that sounds of equal SEL_{cum} produce the equal risk for hearing loss (i.e., if
6 the SEL_{cum} of two sources are similar, a sound from a lower level source with a longer exposure
7 duration may have similar risks to a shorter duration exposure from a higher level source). As has
8 been shown to be the case with humans and terrestrial mammals (Henderson et al. 1991), the
9 EEH does not always hold true within marine mammals due the inherent complexity of predicting
10 threshold shifts (Kastak et al. 2007; Mooney et al. 2009a; Mooney et al. 2009b; Finneran et al.
11 2010a; Finneran et al. 2010b; Finneran and Schlundt 2010). Factors like level (e.g., overall level,
12 sensation level, or level above background), duration, repetition rate (intermittent versus
13 continuous exposure; potential recovery between intermittent periods), number of transient
14 components (short duration and high amplitude), and/or frequency (especially in relation to
15 hearing sensitivity) often are also important factors associated with threshold shifts (e.g., Buck et
16 al. 1984; Clark et al. 1987; Ward 1991; Lataye and Campo 1996). This is especially the case for
17 exposure to impulsive sound sources (Danielson et al. 1991; Henderson et al. 1991; Hamernik et
18 al. 2003), which is why acoustic threshold levels are also expressed as a peak pressure metric
19 (see next section). However, in many cases the EEH approach functions reasonably well as a
20 first-order approximation, especially for higher-level, short-duration sound exposures such as
21 those that are most likely to cause TTS in marine mammals¹⁶.

22 23 24 **2.3.1.1 Recommended Baseline Accumulation Period**

25
26 In order to use the cumulative sound exposure level metric, accumulation time must be specified.
27 Generally, it is predicted that most individuals will only be in the closest ranges to a sound
28 source/activity for a minimal amount of time¹⁷. This is further supported by what is known about
29 behavioral responses to non-lethal human disturbances, with animals typically responding as they
30 would to potential predators (as both have similar costs associated with the perception of risk
31 and/or other fitness consequences; Frid and Dill 2002; Beale and Monaghan 2004; Ford and
32 Reeves 2008; Wirsing et al. 2008; Barber et al. 2010; Wade et al. 2012). Richardson et al. (1995)
33 noted that “avoidance reactions are the most obvious manifestations of disturbance,” and marine
34 mammal literature on behavioral responses to anthropogenic noise support this conclusion
35 (reviewed in Nowacek et al. 2007; Southall et al. 2007). Avoidance of a sound source will
36 ultimately reduce exposure, particularly at the highest sound pressure levels and/or distances
37 closest to the source (Patenaude et al. 2002; DeRuiter et al. 2013). Additionally, mitigation is
38 typically used to reduce the risk of animals receiving levels causing PTS. Thus, individuals
39 closest to the sound source should be detected by marine mammal observers and exposure to
40 the highest sound pressure levels reduced, in turn reducing the likelihood of exposures causing
41 auditory impacts.

42
43 Because of the time component in the SEL_{cum} metric, the use of different types of models to
44 predict sound exposure may necessitate different approaches to evaluating likely effects in the
45 context of the PTS/TTS thresholds. All marine mammals and some sources move in space and
46 time, however, not all models are able to simulate relative source and receiver movement.

¹⁵ The SEL_{cum} metric is being proposed to be applied for discrete activities/sources and not meant to accumulate sound exposure for multiple activities occurring within the same area or over the same time.

¹⁶ It is valuable for applicants, if possible, to indicate under what conditions these acoustic threshold levels will be exceeded.

¹⁷ Gedamke et al. 2011 modeled seismic exposure scenarios and found “cumulative SEL is primarily going to be dictated by the relatively few highest SELs from individual shots that the whale encounters.”

1 Additionally, some models are able to predict the received level of sound at each modeled animal
2 (often called animats) and accumulate sound at these receivers while incorporating the changing
3 model environment. For applicants/users that have the ability to model moving animals and/or
4 sources and the accumulating sound at each receiver, NOAA proposes that 24-hours or the
5 length of activity, whichever is less, be used as the accumulation time. 24 hours has been used in
6 other noise assessment planning applications (e.g., community noise planning for aircraft,
7 vehicular traffic, and railway noise) and provides a reasonable outer bound in situations where
8 the model will be able reflect realistic changes in relative distance between the source and likely
9 exposed marine mammals over the course of a day.

10
11 However, for models that do not incorporate animal movement, it is not appropriate to make the
12 assumption that animals will remain at a constant distance from the source accumulating acoustic
13 energy for 24 hours. Additionally, if sound accumulation cannot be modeled, an alternative
14 method must be used. For situations where modelling of movement and sound accumulation are
15 not possible, an alternate method that is intended to address the accumulation of sound energy
16 over time, but instead provides a distance from the source (“SEL threshold distance”) that is
17 simpler to apply in exposure modeling (i.e., would be used in calculations in the same way
18 distance is used to calculate exposures above previous NOAA sound pressure level thresholds)
19 should be used. Based on what we know about typical animal movement and avoidance, we
20 propose a 1-hour accumulation period be used to calculate the “SEL threshold distance”. This
21 “SEL threshold distance” is calculated by determining the distance from the source at which an
22 animal would have to remain for 1 hour in order to accumulate sound to the designated threshold.
23 While, animals may move closer and farther from the source, this distance is considered a
24 reasonable and conservative approximation.

25
26 The 24-hour (for models able to account for movement and sound accumulation) and 1-hour (for
27 models not able to account for movement and sound accumulation) accumulation periods are
28 considered a conservative baseline for accumulation time under most situations. The use of
29 models able to account for movement and sound accumulation may also allow for the inclusion of
30 additional details to provide a more realistic results based on the accumulation of sound (e.g.
31 information on residence time of individuals, swim speeds for transient species, or specific times
32 when activity temporarily ceases). Alternatively, there may be case-specific circumstances where
33 the 1-hour accumulation time should be modified to account for situations where animals are
34 expected to be in closer proximity to the source over a notably longer amount of time, based on
35 activity, site, and species-specific information (e.g., where there is a resident population in a small
36 and/or confined area and a long-duration activity with a large sound source, or a continuous
37 stationary activity nearby a pinniped pupping beach).

40 **2.3.2 Peak Pressure Metric**

41
42 Sound exposure containing transient components (e.g., short duration and high amplitude;
43 impulsive sounds) can create a greater risk of causing direct mechanical fatigue (as opposed to
44 strictly metabolic) to the inner ear compared to sounds that are strictly non-impulsive (Henderson
45 and Hamernik 1986; Levine et al. 1998; Henderson et al. 2008). Often the risk of damage from
46 these transients does not depend on the duration of exposure (e.g., concept of “critical level,”
47 where damage switches from being primarily metabolic to more mechanical; short duration of
48 impulse can be less than the ear’s integration time, leading to the potential to damage beyond the
49 level the ear can perceive (Akay 1978)). Human noise standards recognize and some provide
50 separate acoustic threshold levels for impulsive sound sources (Occupational Safety and Health
51 Administration (OSHA) 29 CFR 1910.95; Starck et al. 2003). Thus, SEL_{cum} is not an appropriate
52 metric to capture these effects (i.e., often violates EEH; NIOSH 1998), which is why
53 instantaneous peak sound pressure level has also been chosen as part of NOAA’s dual acoustic
54 threshold levels. Auditory weighting is not considered appropriate for use with this metric, as
55 direct mechanical damage associated with sounds having high peak pressures typically does not

1 strictly reflect the frequencies an individual species hears best (Ward 1962; Saunders et al. 1985;
2 ANSI 1986; DOD 2004; OSHA 29 CFR 1910.95).

3 4 5 **2.3.3 Comparison Among Metrics** 6

7 NOAA's previous acoustic threshold levels are expressed as root-mean-square (dB_{rms}), which
8 uses a different metric from peak sound pressure levels (dB_{peak}) and SEL_{cum} that are being
9 recommended for our TTS and PTS onset acoustic threshold levels. Thus, we recommend
10 caution when comparing past acoustic threshold levels to the acoustic threshold levels presented
11 in this document as because they are based on different metrics, they are not directly
12 comparable. For example, a $180 \text{ dB}_{\text{rms}}$ level is not equal to a $180 \text{ dB}_{\text{peak}}$ level. Furthermore, the
13 SEL_{cum} metric incorporates time and is an energy level with a different reference value (re: $1 \mu\text{Pa}^2\text{-}$
14 s), thus it is not directly comparable to other metrics that describe sound pressure levels (re: 1
15 μPa).

16 17 18 **2.3.4 Development of TTS and PTS Onset Acoustic Threshold Levels** 19

20 NOAA's development of the TTS and PTS onset acoustic threshold levels, consisted of the
21 following steps (for specific details on each of the steps used to derive these acoustic threshold
22 levels, see Appendix B.):
23

- 24 1. Identification of available data on hearing loss associated with acoustic threshold in
25 marine mammals (e.g., Google Scholar, Web of Knowledge, Southall et al. 2007,
26 references in listed in available reports/publications).
- 27 2. Evaluation and summary of currently available, published data (26 studies found in Table
28 5) on hearing loss associated with noise exposure in marine mammals.
 - 29 • Because no published data exist on PTS in marine mammals, TTS onset data
30 were evaluated and summarized in order to extrapolate to PTS onset.
 - 31 • Studies were summarized by dividing them into the following categories based
32 on characteristics of the sound at the source (i.e., not characteristics at the
33 receiver) and functional hearing group studied:
 - 34 ○ Impulsive¹⁸ sources (transient, brief (less than 1 second), broadband,
35 and typically consist of high peak pressure with rapid rise time and rapid
36 decay (ANSI 1986; NIOSH 1998; ANSI 2005)) vs. Non-impulsive sources
37 (can be broadband, narrowband or tonal, brief or prolonged, continuous
38 or intermittent) and typically do not have a high peak pressure with rapid
39 rise time (typically only small fluctuations in dB level) that impulsive
40 signals do (ANSI 1995; NIOSH 1998).
 - 41 ○ Marine mammal functional hearing groups: LF Cetaceans, MF
42 Cetaceans, HF Cetaceans, Phocid Pinnipeds, and Otariid Pinnipeds.
- 43 3. Determination of TTS onset (RLs, both in peak pressure and SEL_{cum} metrics) for each
44 individual where data were available.
- 45 4. Implementation of appropriate marine mammal weighting function to data (SEL_{cum} metric
46 acoustic threshold level only).
- 47 5. Final determination TTS onset for each sound category and by each marine mammal
48 functional hearing group.

¹⁸ Note the definition of impulsive in this document relates specifically to noise-induced hearing loss and specifies the physical characteristics of a sound source, which likely gives them a higher potential to cause injury. This definition captures how these sound types may be more likely to affect auditory physiology. These definitions are not meant, however, to reflect how sounds have previously been characterized for behavior under NOAA's 120 and 160 dB MMPA thresholds.

1
2
3
4
5
6
7
8
9

- Established protocol (Table B7) for combining data from multiple individuals or use of surrogates when no data were available within a certain category.
6. Extrapolation for PTS onset (in both peak pressure and SELcum metrics) based on data from humans and terrestrial mammals.

Table 5: Currently available underwater marine mammal threshold shift peer reviewed studies.

References in Chronologic Order ⁺	Sound Source (Sound Source Category)	Sound-Exposed Species (number of individuals [^])
Kastak et al. 1999	Octave-band noise (non-impulsive)	California sea lion (1), northern elephant seal (1), & harbor seal (1)
Finneran et al. 2000	Explosion simulator (impulsive)*	Bottlenose dolphin (2) & beluga (1)
Schlundt et al. 2000	Tones (non-impulsive)	Bottlenose dolphin (5) & beluga (2)
Finneran et al. 2002	Seismic watergun (impulsive)	Bottlenose dolphin (1) & beluga (1)
Finneran et al. 2003	Arc-gap transducer (impulsive)*	California sea lion (2)
Nachtigall et al. 2003	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Nachtigall et al. 2004	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Finneran et al. 2005	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. 2007	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)
SEAMARCO 2011 ⁺	Impact pile driving (impulsive)	Harbor porpoise (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 ⁺	Impact pile driving (impulsive)	Harbor seal (2)
Kastelein et al. 2013b	Octave-band noise (non-impulsive)	Harbor seal (1)
Kastelein et al. 2013c	Tone (non-impulsive)	Harbor porpoise (1)

⁺ Peer reviewed studies available and evaluated as of 30 November 2013. Note there are two papers expected to publish in the near future and are currently taken into account in this document. However for both these studies, TTS onset could not be induced. Thus, neither study affects the proposed acoustic threshold levels and are instead included for completeness.

[^] Note, some individuals have been used in multiple studies.

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

10
11

1
2
3
4

**Table 6: a. Summary of TTS and PTS onset dual acoustic threshold levels.
b. Other factors for considerations based on frequency and duration of exposure.**

a. Numeric Level**				
	PTS Onset (Received Level)		TTS Onset (Received Level)	
Hearing Group	Impulsive	Non-impulsive	Impulsive	Non-impulsive
Low-Frequency (LF) Cetaceans	<i>Cell 1</i> 230 dB _{peak} & 187 dB SEL _{cum}	<i>Cell 2</i> 230 dB _{peak} & 198 dB SEL _{cum}	<i>Cell 11</i> 224 dB _{peak} & 172 dB SEL _{cum}	<i>Cell 12</i> 224 dB _{peak} & 178 dB SEL _{cum}
Mid-Frequency (MF) Cetaceans	<i>Cell 3</i> 230 dB _{peak} & 187 dB SEL _{cum}	<i>Cell 4</i> 230 dB _{peak} & 198 dB SEL _{cum}	<i>Cell 13</i> 224 dB _{peak} & 172 dB SEL _{cum}	<i>Cell 14</i> 224 dB _{peak} & 178 dB SEL _{cum}
High-Frequency (HF) Cetaceans	<i>Cell 5</i> 201 dB _{peak} & 161 dB SEL _{cum}	<i>Cell 6</i> 201 dB _{peak} & 180 dB SEL _{cum}	<i>Cell 15</i> 195 dB _{peak} & 146 dB SEL _{cum}	<i>Cell 16</i> 195 dB _{peak} & 160 dB SEL _{cum}
Phocid Pinnipeds (Underwater)	<i>Cell 7</i> 235 dB _{peak} & 192 dB SEL _{cum}	<i>Cell 8</i> 235 dB _{peak} & 197 dB SEL _{cum}	<i>Cell 17</i> 229 dB _{peak} & 177 dB SEL _{cum}	<i>Cell 18</i> 229 dB _{peak} & 183 dB SEL _{cum}
Otariid Pinnipeds (Underwater)	<i>Cell 9</i> 235 dB _{peak} & 215 dB SEL _{cum}	<i>Cell 10</i> 235 dB _{peak} & 220 dB SEL _{cum}	<i>Cell 19</i> 229 dB _{peak} & 200 dB SEL _{cum}	<i>Cell 20</i> 229 dB _{peak} & 206 dB SEL _{cum}

* Dual acoustic threshold levels: Use whichever level [dB_{peak} or dB SEL_{cum}] exceeded first. All SEL_{cum} acoustic threshold levels (re: 1 μPa²-s) are weighted. Note that acoustic threshold levels for impulsive or non-impulsive sources are based on characteristics at the source and not the receiver.

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

Additional Detail Regarding Data Used to Derive Acoustic Threshold Levels:

Cells 1 through 10: Acoustic threshold level (peak and SEL_{cum}) based on an extrapolation, using related data (when available), rather than direct measurements. All PTS onset acoustic threshold levels are extrapolations based on terrestrial and limited marine mammal growth rate data.

Cell 11: Direct measurements of TTS onset do not exist. Mid-frequency cetaceans are used as surrogates for peak and SEL_{cum} acoustic threshold levels.

Cell 12: Direct measurements of TTS onset do not exist. Mid-frequency cetaceans are used as surrogates for peak and SEL_{cum} acoustic threshold levels.

Cell 13: Peak pressure and SEL_{cum} acoustic threshold levels are based on data from a beluga exposed to a seismic watergun (Finneran et al. 2002).

Cell 14: Peak pressure is based on data from a beluga exposed to a seismic watergun (Finneran et al. 2002). The SEL_{cum} level is based on data from bottlenose dolphins (n=6) exposed to either octave-band noise or tones (Schlundt et al. 2000; Mooney et al. 2009a; Finneran et al. 2010a; Finneran and Schlundt 2010). For bottlenose dolphins: median = 178 dB SEL_{cum}, 1st quartile = 175.5 dB SEL_{cum}, 3rd quartile = 181.6 dB SEL_{cum}. Median level also supported by beluga data (Schlundt et al. 2000).

Cell 15: Peak pressure and SEL_{cum} acoustic threshold levels are based on data from a harbor porpoise exposed to airgun shots (Lucke et al. 2009).

Cell 16: Peak pressure level is based on data from a harbor porpoise exposed to airgun shots (Lucke et al. 2009). The SEL_{cum} is based on data from a harbor porpoise exposed to octave-band noise (Kastelein et al. 2012b).

Cell 17: Direct measurements of TTS onset for this type of sound source do not exist. The SEL_{cum} and peak pressure acoustic threshold level are based on an extrapolation from methodology derived from Southall et al. 2007.

Cell 18: Peak pressure level is based on an extrapolation from methodology derived from Southall et al. 2007, since no direct measurements exist. The SEL_{cum} is based on data from a harbor seal (n=1) exposed to octave-band noise (Kastak et al. 2005).

Cell 19: Direct measurements of TTS onset for this type of sound source do not exist. The SEL_{cum} is based on an extrapolation from methodology derived from Southall et al. 2007. Phocid extrapolation is used as a surrogate for the peak pressure level, since extrapolation produces unrealistic results.

Cell 20: The SEL_{cum} is based on data from a California sea lion (n=1) exposed to octave-band noise (Kastak et al. 2005). Phocid extrapolation is used as a surrogate for the peak pressure level, since extrapolation produces unrealistic results.

5
6

b. Qualitative Factors for Considerations⁺: Frequency and Duration of Exposure	
Frequency[^]:	
<u>General Trend Identified:</u>	
1) Growth of threshold shift (TS): Growth rates of TS (dB of TTS/dB noise) are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010)	
Duration:	
<u>General Trends Identified:</u>	
1) Violation of Equal Energy Hypothesis: Non-impulsive, intermittent exposures require higher SEL _{cum} to induce TS compared to continuous exposures of the same duration (Mooney et al. 2009a; Finneran et al. 2010b)	
2) Violation of Equal Energy Hypothesis: Exposures of longer duration and lower levels induce TTS at a lower level than those exposures of higher level (below the critical level) and shorter duration with the same SEL _{cum} (Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a)	
3) Recovery from TS: With the same SEL _{cum} , longer exposures require longer durations to recover (Mooney et al. 2009b; Finneran et al. 2010a)	
4) Recovery from TS: Intermittent exposures recover faster compared to continuous exposures of the same duration (Finneran et al. 2010b)	
⁺ Although these descriptions do not provide a direct means for quantifying general trends (i.e., all cited studies are based on a limited number of species and individuals), they may be useful within a larger assessment.	
[^] Frequency dependent hearing loss (i.e., PTS) is taken into account, quantitatively, with frequency weighting functions.	

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

1
2
3
4

Table 7: Alternative PTS and TTS onset dual acoustic threshold levels for applicants unable to incorporate auditory weighting functions* (i.e., all acoustic threshold levels are unweighted).

Numeric ⁺ Level				
	PTS Onset (Received Level)		TTS Onset (Received Level)	
Hearing Group	Impulsive	Non-Impulsive	Impulsive	Non-Impulsive
Low-Frequency (LF) Cetaceans	Source: All 230 dB _{peak} & 187 dB SEL _{cum}	Source: NB ≥ 10 kHz 230 dB _{peak} & 215 dB SEL _{cum}	Source: All 224 dB _{peak} & 172 dB SEL _{cum}	Source: NB ≥ 10 kHz 224 dB _{peak} & 195 dB SEL _{cum}
		Source: All others 230 dB _{peak} & 198 dB SEL _{cum}		Source: All others 224 dB _{peak} & 178 dB SEL _{cum}
Mid-Frequency (MF) Cetaceans	Source: All 230 dB _{peak} & 204 dB SEL _{cum}	Source: NB ≥ 3 kHz 230 dB _{peak} & 198 dB SEL _{cum}	Source: All 224 dB _{peak} & 189 dB SEL _{cum}	Source: NB ≥ 3 kHz 224 dB _{peak} & 178 dB SEL _{cum}
		Source: All others 230 dB _{peak} & 215 dB SEL _{cum}		Source: All others 224 dB _{peak} & 195 dB SEL _{cum}
High-Frequency (HF) Cetaceans	Source: All 201 dB _{peak} & 180 dB SEL _{cum}	Source: NB ≥ 3 kHz 201 dB _{peak} & 180 dB SEL _{cum}	Source: All 195 dB _{peak} & 165 dB SEL _{cum}	Source: NB ≥ 3 kHz 195 dB _{peak} & 160 dB SEL _{cum}
		Source: All others 201 dB _{peak} & 199 dB SEL _{cum}		Source: All others 195 dB _{peak} & 179 dB SEL _{cum}
Phocid Pinnipeds (Underwater)	Source: All 235 dB _{peak} & 192 dB SEL _{cum}	Source: All 235 dB _{peak} & 197 dB SEL _{cum}	Source: All 229 dB _{peak} & 177 dB SEL _{cum}	Source: All 229 dB _{peak} & 183 dB SEL _{cum}
Otariid Pinnipeds (Underwater)	Source: All 235 dB _{peak} & 215 dB SEL _{cum}	Source: All 235 dB _{peak} & 220 dB SEL _{cum}	Source: All 229 dB _{peak} & 200 dB SEL _{cum}	Source: All 229 dB _{peak} & 206 dB SEL _{cum}

* Dual acoustic threshold levels: Use whichever [dB_{peak} or dB SEL_{cum}] exceeded first. These alternative acoustic threshold levels are based on whether the sound pressure levels from the source are predominantly within the “M-weighting” component of the curve, or the EQL portion of the auditory weighting curve (i.e., below or above 3 kHz for MF and HF cetaceans and 10 kHz for LF cetaceans, respectively). Since pinniped auditory weighting functions are derived solely from the M-weighting function, the same exposure levels are used for all sound sources. They also are based on an assumption that the most common of impulsive sources (i.e., airguns, impact pile drivers, explosives) have the majority of their sound pressure level at low frequencies (i.e., within the M-weighted component of the curve for HF and MF cetaceans: below 3 kHz). If there were an impulsive source with the majority of its energy above 3 kHz, the proposed alternative criteria would need to be modified on a case-by-case basis.

Note that acoustic threshold levels for impulsive or non-impulsive sources are based on characteristics at the source and not the receiver.

+ Other qualitative factors for considerations presented in Table 6b should still be considered in conjunction with these acoustic threshold levels

5
6
7
8
9
10
11

1 **III. REGULATORY CONTEXT FOR AUDITORY IMPACT ACOUSTIC**
2 **THRESHOLD LEVELS FOR MARINE MAMMALS**
3

4 NOAA has compiled, interpreted and synthesized the best available science to produce new
5 thresholds for the onset of both temporary and permanent hearing threshold shift (“TTS” and
6 “PTS”, respectively) in marine mammals from underwater sound. In the regulatory context,
7 NOAA uses this information to help quantify “take” and to conduct more comprehensive effects
8 analyses under several statutes.
9

10 *Marine Mammal Protection Act and Endangered Species Act.* NOAA equates the onset of
11 permanent threshold shift (PTS), which is an auditory injury, with “Level A Harassment” as
12 defined in the Marine Mammal Protection Act (MMPA) and with “harm” as defined in Endangered
13 Species Act (ESA) regulations, such that exposing an animal to weighted received sound levels
14 at or above the indicated PTS threshold is considered to result in these two types of “take.”
15

16 As explained below, NOAA does not consider temporary threshold shift (TTS) to be an auditory
17 injury and thus it does not qualify as Level A harassment or harm. Nevertheless, TTS is an
18 adverse effect that constitutes another kind of “take” under those statutes: “Level B harassment”
19 under the MMPA and “harassment” under the ESA. MMPA Level B harassment and ESA
20 harassment are broad categories that encompass not only TTS but also other effects such as
21 behavioral impacts, which almost always involve a lower onset threshold than that for onset of
22 TTS. In quantifying take by Level B harassment or harassment, NOAA considers *all* effects that
23 fall into those categories of take, not just TTS. NOAA currently is in the process of developing
24 new thresholds for onset of behavioral effects. When that process is completed, TTS will be
25 addressed for purposes of take quantification. In the meantime, the TTS thresholds presented
26 represent the best available science and will be used in the comprehensive effects analyses
27 under the MMPA and the ESA and may inform the development of mitigation and monitoring.
28

29 *National Marine Sanctuaries Act.* The broad definition of “injury” under the National Marine
30 Sanctuaries Act (NMSA) regulations includes both PTS and TTS (as well as other adverse
31 changes in physical or behavioral characteristics that are not addressed in this document).
32
33

34 **3.1 Background: Applicable Statutory and Regulatory Standards, Definitions and**
35 **Processes**
36

37 **3.1.1 Marine Mammal Protection Act**
38

39 The MMPA prohibits the take of marine mammals, with certain exceptions, one of which is the
40 issuance of incidental take authorizations (ITAs). Sections 101(a)(5)(A) & (D) of the MMPA (16
41 U.S.C. 1361 *et seq.*) direct the Secretary of Commerce to allow, upon request, the incidental, but
42 not intentional, taking of small numbers of marine mammals by U.S. citizens who engage in a
43 specified activity (other than commercial fishing) within a specified geographical region if certain
44 findings are made. Through delegation by the Secretary of Commerce, NMFS is required to
45 authorize the incidental taking of marine mammals if it finds that the total taking will have a
46 negligible impact on the species or stock(s) and will not have an unmitigable adverse impact on
47 the availability of the species or stock(s) for certain subsistence uses. NMFS must also set forth
48 the permissible methods of taking and requirements pertaining to the mitigation, monitoring, and
49 reporting of such takings. (The “small numbers” and “specified geographical region” provisions do
50 not apply to military readiness activities.)
51

52 The term “take” means to harass, hunt, capture, or kill, or attempt to harass, hunt, capture or kill
53 any marine mammal. 16 U.S.C. § 1362(13).
54

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

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

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

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

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

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

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

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

- The **type** of incidental taking authorization that is being requested (i.e., takes by Level B Harassment only; **Level A Harassment**, or serious injury/mortality) and the method of incidental taking;
- By age, sex, and reproductive condition (if possible), the **number** of marine mammals (by species) that may be taken **by each type** of taking identified in paragraph (a)(5) of this section, and the number of times such takings by each type of taking are likely to occur.

50 CFR § 216.104 (emphasis added).

3.1.2 Endangered Species Act

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

“Take” means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct. See *id.* at § 1532(19). “Harm” is defined in NMFS

1 regulations as “an act which actually kills or injures fish or wildlife” (and can include significant
2 habitat modification or degradation). See 50 C.F.R. § 222.102.

3
4 Under NMFS’s and the USFWS’s implementing regulations for Section 7 of the ESA, “jeopardize
5 the continued existence of” means to engage in an action that reasonably would be expected,
6 directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of a
7 listed species in the wild by reducing the reproduction, numbers, or distribution of that species.
8 See *id.* at § 402.02.

9
10 In support of the analysis necessary to conduct the consultation, the ESA implementing
11 regulations state that in order to initiate formal consultation, the federal action agency must
12 submit a written request for formal consultation to the Director (of NMFS or the USFWS) that
13 includes, among other things, a description of the manner in which the action may affect any
14 listed species. See *id.* at § 402.14(c).

15 16 17 **3.1.3 National Marine Sanctuaries Act**

18
19 Section 304(d) of the NMSA requires federal agencies whose actions are likely to destroy, cause
20 the loss of, or injure a sanctuary resource to consult with the Office of National Marine
21 Sanctuaries (ONMS) before taking the action. See 16 U.S.C. § 1434(d)(1). The NMSA defines
22 sanctuary resource as “any living or nonliving resource of a national marine sanctuary that
23 contributes to the conservation, recreational, ecological, historical, educational, cultural,
24 archeological, scientific, or aesthetic value of the sanctuary.” 16 U.S.C. § 1432(8). Through the
25 sanctuary consultation process, ONMS may recommend reasonable and prudent alternatives that
26 will protect sanctuary resources. Recommended alternatives may include alternative locations,
27 timing, and/or methods for conducting the proposed action. See *id.* at § 1434(d)(2). Monitoring
28 may also be recommended to better characterize impacts to sanctuary resources or accompany
29 mitigation. See *id.*

30
31 The term “injure” is defined in the ONMS implementing regulations as to “change adversely,
32 either in the short or long term, a chemical, biological or physical attribute of, or the viability of.”
33 15 C.F.R. § 922.3

34
35 In support of the analysis necessary to conduct the consultation, the NMSA requires that any
36 federal agency proposing an action that may injure a sanctuary resource provide ONMS with a
37 written statement (“sanctuary resource statement”) describing the action and its potential effects
38 on sanctuary resources. See 16 U.S.C. § 1434(d)(1)(B).

39 40 41 **3.2 Application of Permanent Threshold Shift Acoustic Threshold Levels**

42
43 The acoustic thresholds for PTS will be used in conjunction with sound source characteristics,
44 environmental factors that influence sound propagation, anticipated marine mammal occurrence
45 and behavior in the vicinity of the activity, as well as other available activity-specific factors, to
46 estimate (acknowledging the gaps in scientific knowledge and the inherent uncertainties in a
47 marine environment) the number of takes of marine mammals (Level A harassment and harm
48 under the MMPA and ESA, respectively) and facilitate compliance with the MMPA, ESA, and
49 NMSA as described above.

50
51 NOAA will use the same PTS thresholds in the identification and quantification of MMPA Level A
52 harassment for both military readiness and non-military readiness activities. Because the
53 acoustic thresholds for PTS predict the *onset* of PTS, they are inclusive of the “potential” and
54 “significant potential” language in the two definitions of Level A harassment. The limited data now
55 available do not support the parsing out of a meaningful quantitative difference between the

1 “potential” and “significant potential” for injury and, therefore, the designated PTS thresholds will
2 be treated as Level A harassment for both types of activities.
3

4 Estimating the numbers of take by Level A harassment and harm is one piece of the fuller
5 analyses that inform NOAA’s “negligible impact” and “jeopardy” determinations under the MMPA
6 and ESA, respectively, as well as “likely to injure” or “may affect” determinations under the
7 NMSA. Last, the PTS thresholds may be used to inform the development of mitigation and
8 monitoring measures (such as shut-down zones) pursuant to the MMPA, ESA, or NMSA.
9

10 When initiating any of the MMPA, ESA, or NMSA processes described above, agencies and other
11 applicants should utilize the PTS thresholds and methods outlined in Section II of this document,
12 in combination with activity-specific information, to predict whether, and if so how many, instances
13 of PTS are expected to occur.
14

15 16 **3.2.1 Temporary Threshold Shift Acoustic Threshold Levels** 17

18 NOAA does not consider TTS an auditory injury based on the work of a number of investigators
19 that have measured TTS before and after exposure to intense sound. For example, Ward (1997)
20 suggested that TTS is within the normal bounds of physiological variability and tolerance and
21 does not represent physical injury. In addition, Southall et al. (2007) indicates that although PTS
22 is a tissue injury, TTS is not because the reduced hearing sensitivity following exposure to
23 intense sound results primarily from fatigue, not loss, of cochlear hair cells and supporting
24 structures, and is reversible. Accordingly, NMFS does not consider TTS as Level A harassment
25 under the MMPA or harm under the ESA. Rather, TTS is considered take by Level B harassment
26 under the MMPA and harassment under the ESA, which will be the subject of future guidance.
27 However, TTS (along with PTS and behavioral impacts) is considered injury under the broad
28 definition of the term “injury” in NMSA regulations.
29

30 NOAA is aware of recent studies by Kujawa and Liberman (2009) and Lin et al. (2011), which
31 found that despite completely reversible threshold shifts that leave cochlear sensory cells intact,
32 large (but temporary) threshold shifts could cause synaptic level changes and delayed cochlear
33 nerve degeneration in mice and guinea pigs, respectively. However, these large TTSs that led to
34 the synaptic changes shown in these studies are in the range of the large TTSs used in Southall
35 et al. (2007) and here to calculate PTS thresholds. It is not known whether smaller levels of TTS
36 would lead to similar changes. NOAA acknowledges the complexity of noise exposure on the
37 nervous system, and will re-examine this issue as more data become available.
38

39 The occurrence of, and estimated number of, TTS takes is one piece of the larger analysis that
40 informs NOAA’s “negligible impact” and “jeopardy” determinations under the MMPA and ESA,
41 respectively, as well as “likely to injure” or “may affect” determinations under the NMSA. TTS
42 thresholds also may be used to inform the development of mitigation and monitoring measures
43 pursuant to the MMPA, ESA, or NMSA.
44

45 Note: This document constitutes a statement of NOAA’s current practice for assessing Level A
46 Harassment and harm pursuant to the MMPA and ESA, respectively, and one kind of injury under
47 the NMSA, from auditory impacts. NOAA recommends that Federal agencies and prospective
48 applicants evaluating these types of impacts for the purposes of engaging in the aforementioned
49 statutory processes also use these thresholds in the manner described here. However, this
50 guidance does not create or confer any rights for or on any person, or operate to bind the public.
51 An alternative approach may be proposed (by Federal agencies or prospective applicants) and
52 used if case-specific information/data indicate that the alternative approach is likely to produce a
53 more accurate estimate of Level A Harassment, harm, or auditory injury for the project being
54 evaluated and if NOAA determines the approach satisfies the requirements of the applicable
55 statutes and regulations.
56

1 **IV. UPDATE OF ACOUSTIC GUIDANCE AND ACOUSTIC THRESHOLD LEVELS**

2
3 Research on the effects of anthropogenic sound on marine mammals has increased dramatically
4 since the inception of NOAA's previous acoustic threshold levels, and will likely continue to
5 increase in the future. As such, this document will be reviewed periodically and updated as
6 appropriate to reflect the best available science.

7
8 NOAA's initial approach for updating current acoustic threshold levels consisted of providing
9 acoustic thresholds for underwater PTS and TTS onset for marine mammals. As more data
10 become available, acoustic thresholds may be established for additional protected species, such
11 as sea turtles and marine fishes. As with this document, public review and outside peer review
12 will be integral to the development and refinement of acoustic thresholds.

13
14
15 **4.1 Procedure and Timeline for Updating Acoustic Thresholds**

16
17 NOAA will convene staff from our various offices, regions, and science centers, and re-evaluate
18 and update acoustic threshold levels at least every three to five years as new data become
19 available and as deemed appropriate. In addition to evaluating new, relevant scientific studies,
20 NOAA will also periodically re-examine basic concepts and definitions (e.g., functional hearing
21 groups, PTS, TTS, weighting functions), appropriate metrics, data standards, protocols for
22 accounting for uncertainty, temporal and spatial considerations, and other relevant topics.
23 Updates will be posted at <http://www.nmfs.noaa.gov/pr/acoustics/>

**APPENDIX A: MARINE MAMMAL AUDITORY WEIGHTING FUNCTION
AMPLITUDES**

Marine mammal auditory weighting functions are described in the main body of this document (i.e., Section 2.2). This appendix provides broad weighting function amplitudes (calculated directly from the proposed auditory weighting functions) (Tables A1 to A5).

Table A1: Low-frequency cetacean auditory weighting function amplitudes.*

Frequency (Hz)	Weighting Function Amplitude
7.5	-22 dB
10	-20 dB
20	-17 dB
50	-10 dB
100	-4 dB
250	-1 dB
500	0 dB
1000	0 dB
3000	-3 dB
4000	-6 dB
6000	-10 dB
10000	-17 dB
20000	-20 dB
30000	-23 dB

*Table provides an example of weighting function amplitudes over a broad range of frequencies (i.e., not an exhaustive compilation of all amplitudes at all frequencies)

1
2

Table A2: Mid-frequency cetacean auditory weighting function amplitudes.*

Frequency (Hz)	Weighting Function Amplitude
100	-27 dB
500	-17 dB
1000	-17 dB
3000	-17 dB
6000	-7 dB
10000	-3 dB
20000	0 dB
30000	0 dB
40000	0 dB
50000	-1 dB
60000	-2 dB
70000	-2 dB
80000	-3 dB
90000	-4 dB
100000	-5 dB
110000	-6 dB
120000	-7 dB
130000	-8 dB
140000	-9 dB
150000	-9 dB
160000	-10 dB

*Table provides an example of weighting function amplitudes over a broad range of frequencies (i.e., not an exhaustive compilation of all amplitudes at all frequencies)

3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

1
2

Table A3: High-frequency cetacean auditory weighting function amplitudes.*

Frequency (Hz)	Weighting Function Amplitude
100	-33 dB
500	-21 dB
1000	-20 dB
3000	-19 dB
4000	-15 dB
6000	-9 dB
10000	-4 dB
20000	-1 dB
30000	0 dB
40000	0 dB
50000	-1 dB
60000	-1 dB
70000	-2 dB
80000	-2 dB
90000	-3 dB
100000	-4 dB
110000	-5 dB
120000	-6 dB
130000	-6 dB
140000	-7 dB
150000	-8 dB
160000	-9 dB
170000	-9 dB
180000	-10 dB

*Table provides an example of weighting function amplitudes over a broad range of frequencies (i.e., not an exhaustive compilation of all amplitudes at all frequencies)

3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

1
2

Table A4: Phocid auditory weighting function amplitudes.*

Frequency (Hz)	Weighting function amplitude
50	-10 dB
100	-4 dB
500	-0 dB
1000	-0 dB
3000	-0 dB
60000	-0 dB
10000	-0 dB
20000	-0 dB
30000	-1 dB
40000	-1dB
50000	-2 dB
60000	-3 dB
70000	-3dB
80000	-4dB
90000	-5 dB
100000	-6 dB

*Table provides an example of weighting function amplitudes over a broad range of frequencies (i.e., not an exhaustive compilation of all amplitudes at all frequencies)

3
4
5
6

Table A5: Otariid auditory weighting function amplitudes.*

Frequency (Hz)	Weighting function amplitude
100	-6 dB
500	-0 dB
1000	-0 dB
3000	-0 dB
6000	-0 dB
10000	-1 dB
20000	-2 dB
30000	-4 dB
40000	-6 dB

*Table provides an example of weighting function amplitudes over a broad range of frequencies (i.e., not an exhaustive compilation of all amplitudes at all frequencies)

7
8
9
10

APPENDIX B: DEVELOPMENT OF ACOUSTIC THRESHOLD LEVELS FOR ONSET OF PERMANENT AND TEMPORARY THRESHOLD SHIFT

This appendix provides detailed information on the development of NOAA’s acoustic threshold levels for onset of permanent and temporary threshold shifts (PTS and TTS), and NOAA’s protocols to address data limitations and uncertainty. Along with dual acoustic threshold levels, qualitative factors such as exposure duration and frequency are proposed for consideration.

NOAA’s proposed TTS and PTS onset acoustic threshold levels are similar to those recently proposed by Finneran and Jenkins (2012). However, the acoustic threshold levels in Tables 6 and 7 (repeated here in Tables B1 and B2) take into account any new TTS data available and follow a protocol for combining multiple datasets (Table B7).

Table B1: a. Summary of TTS and PTS onset dual acoustic threshold levels. b. Other factors for consideration based on frequency and duration of exposure.

a. Numeric Level**				
	PTS Onset (Received Level)		TTS Onset (Received Level)	
Hearing Group	Impulsive	Non-impulsive	Impulsive	Non-impulsive
Low-Frequency (LF) Cetaceans	<i>Cell 1</i> 230 dB _{peak} & 187 dB SEL _{cum}	<i>Cell 2</i> 230 dB _{peak} & 198 dB SEL _{cum}	<i>Cell 11</i> 224 dB _{peak} & 172 dB SEL _{cum}	<i>Cell 12</i> 224 dB _{peak} & 178 dB SEL _{cum}
Mid-Frequency (MF) Cetaceans	<i>Cell 3</i> 230 dB _{peak} & 187 dB SEL _{cum}	<i>Cell 4</i> 230 dB _{peak} & 198 dB SEL _{cum}	<i>Cell 13</i> 224 dB _{peak} & 172 dB SEL _{cum}	<i>Cell 14</i> 224 dB _{peak} & 178 dB SEL _{cum}
High-Frequency (HF) Cetaceans	<i>Cell 5</i> 201 dB _{peak} & 161 dB SEL _{cum}	<i>Cell 6</i> 201 dB _{peak} & 180 dB SEL _{cum}	<i>Cell 15</i> 195 dB _{peak} & 146 dB SEL _{cum}	<i>Cell 16</i> 195 dB _{peak} & 160 dB SEL _{cum}
Phocid Pinnipeds (Underwater)	<i>Cell 7</i> 235 dB _{peak} & 192 dB SEL _{cum}	<i>Cell 8</i> 235 dB _{peak} & 197 dB SEL _{cum}	<i>Cell 17</i> 229 dB _{peak} & 177 dB SEL _{cum}	<i>Cell 18</i> 229 dB _{peak} & 183 dB SEL _{cum}
Otariid Pinnipeds (Underwater)	<i>Cell 9</i> 235 dB _{peak} & 215 dB SEL _{cum}	<i>Cell 10</i> 235 dB _{peak} & 220 dB SEL _{cum}	<i>Cell 19</i> 229 dB _{peak} & 200 dB SEL _{cum}	<i>Cell 20</i> 229 dB _{peak} & 206 dB SEL _{cum}
* Dual acoustic threshold levels: Use whichever level [dB _{peak} or dB SEL _{cum}] exceeded first. All SEL _{cum} acoustic threshold levels (re: 1 µPa ² -s) are weighted. Note that acoustic threshold levels for impulsive or non-impulsive sources are based on characteristics at the source and not the receiver.				
+The SEL _{cum} could be exceeded in multitude of ways (i.e., varying exposure levels and durations). It is valuable for applicants, if possible, to indicate under what conditions these acoustic threshold levels will be exceeded.				

b. Other Factors for Considerations⁺: Duration and Frequency of Exposure	
Frequency[▲]:	
<u>General Trends Identified:</u>	
1) Growth of TTS: Growth rates of threshold shifts (dB of threshold shift/dB noise) are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran 2011)	
Duration:	
<u>General Trends Identified:</u>	
1) Violation of Equal Energy Hypothesis (EEH): Non-impulsive, intermittent exposures require higher SEL _{cum} to induce threshold shifts compared to continuous exposures of the same duration (Mooney et al. 2009a; Finneran et al. 2010b)	
2) Violation of Equal Energy Hypothesis (EEH): Exposures of longer duration and lower levels induce threshold shifts at a lower level than those exposures of higher level* and shorter duration with the same SEL _{cum} (Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein et al. 2012b)	
3) Recovery from threshold shifts: With the same SEL _{cum} , longer exposures require longer durations to recover (Mooney et al. 2009b; Finneran et al. 2010a)	
4) Recovery from threshold shifts: Intermittent exposures recover faster compared to continuous exposures of the same duration (Finneran et al. 2010b)	
⁺ Although these descriptions do not provide a means for quantifying general trends (i.e., all cited studies are based on a limited number of species and individuals), they may be useful within a larger assessment. Additionally, these trends are based specifically on TTS studies.	
[▲] The implementation of weighting functions quantitatively allow for frequency-specific consideration of thresholds shifts.	
* Below the critical level	

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27

Alternative Acoustic Threshold Levels: Without Weighting Functions

TTS and PTS onset acoustic threshold levels consist of both a numerical acoustic threshold level and weighting function. However, NOAA recognizes that the implementation of marine mammal weighting functions represents a new, relatively complex factor for consideration, which may extend beyond the capabilities of some applicants. Thus, NOAA has developed alternative acoustic threshold levels for those who are unable to apply weighting functions (Table B2).

1
2
3

Table B2: Alternative PTS and TTS onset dual acoustic threshold levels (all acoustic threshold levels are unweighted). NB stands for narrowband.

Numeric Level**				
Hearing Group	PTS Onset (Received Level)		TTS Onset (Received Level)	
	Impulsive	Non-Impulsive	Impulsive	Non-Impulsive
Low-Frequency (LF) Cetaceans	Source: All 230 dB _{peak} & 187 dB SEL _{cum}	Source: NB ≥ 10 kHz 230 dB _{peak} & 215 dB SEL _{cum}	Source: All 224 dB _{peak} & 172 dB SEL _{cum}	Source: NB ≥ 10 kHz 224 dB _{peak} & 195 dB SEL _{cum}
		Source: All others 230 dB _{peak} & 198 dB SEL _{cum}		Source: All others 224 dB _{peak} & 178 dB SEL _{cum}
Mid-Frequency (MF) Cetaceans	Source: All 230 dB _{peak} & 204 dB SEL _{cum}	Source: NB ≥ 3 kHz 230 dB _{peak} & 198 dB SEL _{cum}	Source: All 224 dB _{peak} & 189 dB SEL _{cum}	Source: NB ≥ 3 kHz 224 dB _{peak} & 178 dB SEL _{cum}
		Source: All others 230 dB _{peak} & 215 dB SEL _{cum}		Source: All others 224 dB _{peak} & 195 dB SEL _{cum}
High-Frequency (HF) Cetaceans	Source: All 201 dB _{peak} & 180 dB SEL _{cum}	Source: NB ≥ 3 kHz 201 dB _{peak} & 180 dB SEL _{cum}	Source: All 195 dB _{peak} & 165 dB SEL _{cum}	Source: NB ≥ 3 kHz 195 dB _{peak} & 160 dB SEL _{cum}
		Source: All others 201 dB _{peak} & 199 dB SEL _{cum}		Source: All others 195 dB _{peak} & 179 dB SEL _{cum}
Phocid Pinnipeds (Underwater)	Source: All 235 dB _{peak} & 192 dB SEL _{cum}	Source: All 235 dB _{peak} & 197 dB SEL _{cum}	Source: All 229 dB _{peak} & 177 dB SEL _{cum}	Source: All 229 dB _{peak} & 183 dB SEL _{cum}
Otariid Pinnipeds (Underwater)	Source: All 235 dB _{peak} & 215 dB SEL _{cum}	Source: All 235 dB _{peak} & 220 dB SEL _{cum}	Source: All 229 dB _{peak} & 200 dB SEL _{cum}	Source: All 229 dB _{peak} & 206 dB SEL _{cum}

* Dual acoustic threshold levels: Use whichever [dB_{peak} or dB SEL_{cum}] exceeded first. These alternative acoustic threshold levels are based on whether the sound pressure levels from the source are predominantly within the “M-weighting” component of the curve, or the EQL portion of the auditory weighting curve (i.e., below or above 3 kHz for MF and HF cetaceans and 10 kHz for LF cetaceans, respectively). Since pinniped auditory weighting functions are derived solely from the M-weighting function, the same exposure levels are used for all sound sources. They also are based on an assumption that the most common of impulsive sources (i.e., airguns, impact pile drivers, explosives) have the majority of their sound pressure level at low frequencies (i.e., within the M-weighted component of the curve for HF and MF cetaceans: below 3 kHz). If there were an impulsive source with the majority of its energy above 3 kHz, the proposed alternative criteria would need to be modified on a case-by-case basis.

Note that acoustic threshold levels for impulsive or non-impulsive sources are based on characteristics at the source and not the receiver.

+ Other factors for considerations presented in Table B1, b should still be considered in conjunction with these acoustic threshold levels

4
5
6
7
8
9
10
11

These alternative acoustic threshold levels provided are based on when the sound from the source is predominantly within the “M-weighted” or EQL components of the auditory weighting function for cetaceans (i.e., below or above 3 kHz for MF and HF cetaceans and 10 kHz for LF cetaceans). If a sound is within the EQL portion of the curve, the functional hearing group has enhanced hearing sensitivity and susceptibility to noise-induced hearing loss (i.e., PTS or TTS). Since pinniped auditory weighting functions do not have EQL derived components, the same

1 exposure levels are used for all sound sources. The use of these proposed alternative acoustic
2 threshold levels will typically result in higher estimated exposures compared to those that
3 incorporate weighting functions.
4

5 The alternative acoustic threshold levels are based on assumption that the most common
6 impulsive sources (i.e., airguns, impact pile drivers, explosives) and broadband, non-impulsive
7 sounds have the majority of their sound pressure level at low frequencies (i.e., within the M-
8 weighted component for HF and MF cetaceans: ≤ 3 kHz and LF cetaceans: ≤ 10 kHz). If there is
9 an impulsive or a non-impulsive, broadband source with the majority of its sound pressure level
10 above 3 kHz (for MF and HF cetaceans) or 10 kHz (for LF cetaceans), then the alternative
11 acoustic threshold levels would need to be modified (case-by-case basis).
12
13

14 **I. DATA FOR NUMERIC ACOUSTIC THRESHOLD LEVELS BASED ON** 15 **RECEIVED LEVEL** 16

17 Research on the effects of anthropogenic sound on marine mammals has increased dramatically
18 since the inception of NOAA's previous acoustic threshold levels (e.g., Nowacek et al. 2007;
19 Southall et al. 2007). In particular, scientific threshold recommendations have been made for TTS
20 and PTS onset in the Southall et al. (2007) review, as well as in relevant peer-reviewed studies
21 since the review's publication in 2007. NOAA has independently reviewed the recommendations
22 made by Southall et al. (2007), as well as available underwater marine mammal threshold shift
23 studies (26 studies as of 30 November 2013) and their provided data (Table B3).

24 The data in Kastak et al. (2008) did not qualify for inclusion in our analysis, since the data
25 presented in this abstract cannot be validated and verified¹⁹ and/or were not subject to peer
26 review. NOAA is also aware of recent unpublished studies by Kastelein (SEAMARCO 2011;
27 Kastelein et al. 2013a) measuring TTS in a harbor porpoise and two harbor seals exposed to pile
28 driving sounds. NOAA anticipates they will be published in peer-reviewed journals in the near
29 future. As such, these acoustic threshold levels take into account these data.
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52

¹⁹ Verification means that the data and procedures used to produce the scientific information are documented in sufficient detail to allow reproduction of the analysis by others with an acceptable degree of precision, while validation refers to the testing of analytical methods to ensure that they perform as intended (NOAA 2013).

1
2

Table B3: Currently 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. 2005	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. 2007	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)
SEAMARCO 2011 ⁺	Impact pile driving (impulsive)	Harbor porpoise (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 ⁺	Impact pile driving (impulsive)	Harbor seal (2)
Kastelein et al. 2013b	Octave-band noise (non-impulsive)	Harbor seal (1)
Kastelein et al. 2013c	Tone (non-impulsive)	Harbor porpoise (1)

⁺ Peer reviewed studies available and evaluated as of 30 November 2013. Note there are two Kastelein et al. papers expected to publish in the near future and are currently taken into account. However for both these studies ,TTS onset could not be induced. Thus, neither study affects the proposed acoustic threshold levels and are instead included for completeness.

[^] Note, some individuals have been used in multiple studies

* No incidents of temporary threshold shift recorded in study

3
4
5
6
7
8
9
10
11

II. EXPOSURE DURATION AND FREQUENCY

In addition to received level, NOAA recognizes that other factors are also important to consider with the establishment of TTS and PTS onset acoustic threshold levels (i.e., TTS and PTS are complex); namely with regard to exposure duration and exposure frequency. Thus, in addition to numerical acoustic threshold levels based on level, NOAA has provided qualitative factors that it recommends be considered within a broader impact assessment. They are presented as general

1 trends associated with noise-induced hearing loss observed from the limited number marine
2 mammal TTS studies and further supported by human and terrestrial mammal research.
3 Additionally, information on both these factors are summarized in subsequent sections (i.e.,
4 Section IV) of this appendix for completeness. Thus, at this point, for marine mammals these
5 factors are for qualitative consideration (i.e., not enough data to establish numerical acoustic
6 threshold levels based on these additional factors).
7

8 9 **2.1 Exposure Duration**

10 Exposure duration plays a role in the onset of noise-induced hearing loss, as well as recovery
11 from this loss (Table B4). Recent Mooney et al. (2009a, 2009b) studies and the Finneran et al.
12 (2010a) study in bottlenose dolphins and by Kastak et al. (2005, 2007) in pinnipeds indicated that
13 TTS is more likely to occur for those exposures, having the same energy, with longer durations
14 compared to those with short durations. Finneran et al. (2010a) found that sound pressure level
15 and duration were better predictors of TTS than just SEL_{cum} and using SEL_{cum} could result in an
16 underestimation of TTS onset in situations of long-duration exposures, while in situations of short-
17 duration exposures SEL_{cum} could result in an overestimation of TTS onset²⁰. These trends have
18 also been demonstrated in human and terrestrial mammals (e.g., Spieth and Trittipoe 1958; Buck
19 et al. 1984).
20

21
22 NOAA encourages applicants to provide information on the predicted duration of exposure an
23 individual is likely to receive (i.e., are all situations where animals exceed SEL_{cum} acoustic
24 threshold levels associated with a short or extended exposure duration?). Additionally, whether
25 acoustic threshold is intermittent or continuous plays a role in noise-induced hearing loss with
26 animals typically needing to be either closer to the sound source or exposed for a longer duration
27 to induce the same amount of hearing loss compared to those individuals exposed to more
28 continuous sounds (human and terrestrial mammals data: Ward et al. 1958, Clark et al. 1987,
29 Ward 1991; marine mammal data: Mooney et al. 2009b and Finneran et al. 2010b).
30

31 When considering exposure durations for animals under realistic exposure conditions,
32 generally²¹, it is predicted that most individuals will only be in the closest ranges to a noise
33 source/activity for a minimal amount of time (e.g., animals are capable of moving horizontally and
34 vertically in the water column to reduce exposure, and/or individuals are exposed to mobile
35 sources). Thus, using laboratory data from animals exposed to unusually long, continuous
36 durations of noise (i.e., animals cannot leave exposure scenario) may not best reflect scenarios
37 expected to be encountered by wild individuals. For those reasons, NOAA excluded laboratory
38 noise exposures resulting in TTS onset from further analysis if the exposure duration exceeded
39 one hour of continuous exposure.
40

41
42
43
44
45
46
47
48

²⁰ Interestingly, Popov et al. 2011a reported data that are contrary to some of these trends. For example, they reported that acoustic threshold of higher levels and shorter duration were more effective at eliciting higher levels of TTS than those exposures of equal SEL_{cum} but lower levels and longer durations. This highlights the complexity of understanding TTS, especially based on limited data.

²¹ An exception would be situations where resident populations are located in confined areas and/or there is the potential for unusually long exposure

1 **Table B4: Effect of exposure duration on TTS.**
 2

General Trends	Marine Mammal Studies
<u>Intermittence:</u> <ul style="list-style-type: none"> • Intermittent exposures require higher SEL_{cum} to induce TTS compared to continuous exposures of the duration (i.e., intermittent exposure results in lower levels of TTS); Violation of EEH. • Intermittent exposures recover faster compared to continuous exposures of the same duration. • Mean TTS after intermittent exposure was less than mean TTS after continuous exposure of same duration (i.e., cumulative energy approach overestimates growth rate and amount of TTS from intermittent exposures). 	Mooney et al. 2009b; Finneran et al. 2010b Finneran et al. 2010b Finneran et al. 2010b
<u>Duration:</u> <ul style="list-style-type: none"> • Exposures of longer duration and lower levels induce more TTS (onset at lower level; amount of TTS higher) than those exposures of higher level and shorter duration with the same SEL_{cum}; Violation of EEH. • Longer exposures require longer durations to recover compared to shorter duration exposures with the same SEL_{cum}. 	Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein et al. 2012b Mooney et al. 2009a; Finneran et al. 2010a

3
 4
 5 **2.1.1 Recovery**
 6

7 After sound exposure ceases or between successive sound exposures, there is the potential for
 8 recovery from hearing loss (i.e., PTS or TTS, with PTS resulting in incomplete recovery and TTS
 9 resulting in complete recovery). Predicting recovery from sound exposure can be quite
 10 complicated. It can begin rapidly after removal from sound exposure, threshold shifts can
 11 continue to grow before recovery begins, or the onset of recovery can be delayed (Hamernik et
 12 al. 1988). Hearing loss, because of metabolic mechanisms, typically recovers quicker than losses
 13 associated with mechanical mechanisms (Lutz and Hodge 1971; Patuzzi 1998). In general,
 14 threshold shifts of less than 40 dB, in humans and terrestrial mammals, demonstrate more rapid
 15 recovery than thresholds shifts greater than 40 dB (Ward 1960; Miller 1974; Hamernik et al.
 16 1988). This is another reason NOAA chose 40 dB as PTS onset.
 17

18 Some recovery rates from anthropogenic sound exposure have been reported or estimated for
 19 marine mammals after experiencing TTS (Table B5). Note that many of these studies only
 20 induced small amounts of TTS (typically less than 20 dB) and may not be appropriate for
 21 determining recovery rates for larger thresholds shifts. Mooney et al. (2009b) also found the
 22 duration of exposure contributed to rate of recovery, with longer exposures requiring longer
 23 periods to reach full recovery. A recent study by Finneran et al. (2010a) reported that recovery
 24 patterns were complex (e.g., multi-phased recovery pattern).
 25
 26
 27
 28
 29
 30
 31
 32

1
2

Table B5: Existing marine mammal TTS recovery data.

Study	Source	Species	Recovery Period
Kastak et al. 1999; Kastak et al. 2005	Octave-band noise	California sea lion, harbor seal, & Northern elephant seal	Within 24 hours
Schlundt et al. 2000	Tones	Bottlenose dolphin & Beluga	Within 5 hours or less
Finneran et al. 2002	Seismic watergun	Beluga	Within 4 minutes
Nachtigall et al. 2003	Octave-band noise	Bottlenose dolphin	Within 45 minutes
Nachtigall et al. 2004	Octave-band noise	Bottlenose dolphin	Within 105 minutes
Finneran et al. 2005	Tones	Bottlenose dolphin	Within 24 hours
Finneran et al. 2007	Tones	Bottlenose dolphin	Within 4 days
Lucke et al. 2009	Single airgun	Harbor porpoise	Within 55 hours (estimated)
Mooney et al. 2009a	Octave-band noise	Bottlenose dolphin	Within 40 minutes
Mooney et al. 2009b	MFA sonar	Bottlenose dolphin	Within 80 minutes
Popov et al. 2011	Half octave-band noise	Finless porpoise	Within 20 hours
Finneran and Schlundt 2013	Tones	Bottlenose dolphin	Most exposures within 1000 minutes
Popov et al. 2013	Half octave-band noise	Beluga	Within 24 hours
Kastelein et al. 2013b	Octave-band noise	Harbor seal	Within 4 days
Kastelein et al. 2013c	Tone	Harbor porpoise	Within 96 minutes

3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

Based on current data, most recovery occurs within 24 hours of exposure. There are a few exceptions. For example, the longest, measured recovery time was four days from Finneran et al. (2007) (bottlenose dolphin) associated with 30 dB+ of TTS and from Kastelein et al. (2013b) (harbor seal) associated with 44 dB of TTS. The individuals in these studies were exposed at SEL_{cum} at levels above what is being proposed for PTS onset (i.e., even though exposed at level which would exceed our proposed PTS onset acoustic threshold level, the animal still recovered completely).

Currently, recovery in wild marine mammals cannot be accurately quantified. However, Finneran et al. (2010a) and Finneran and Schlundt (2013) propose models 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 these acoustic threshold levels, NOAA assumes for intermittent, repeated exposure that there is no recovery between subsequent exposures (this is especially important for PTS and TTS onset acoustic threshold levels using energy metrics), although it has been demonstrated in terrestrial mammals (Clark et al. 1987; Ward 1991) and recently in a marine mammal study (Finneran et al. 2010b), that there is a reduction in damage and hearing loss with intermittent exposures.

1 **2.2 Frequency**

2
3 There are some general trends associated with hearing loss and the frequency associated with
4 exposure (Table B6). The relationship between “best hearing” and the anthropogenic sound
5 exposure becomes important in context of sensation level (sound level referenced to the
6 individual’s baseline threshold; Yost 2007), with susceptibility to sound typically increasing in
7 regions where one’s hearing is most sensitive (Miller 1974). Finneran et al. (2007) concluded that
8 sensation level played a role in the results they recorded demonstrating higher levels of TTS in
9 dolphins exposed to 20 kHz tones compared to 3 kHz tones (20 kHz tones closer to “best
10 hearing” range compared to 3 kHz tones) but cautioned that other factors may have contributed,
11 as well. Nevertheless, they indicated “a need for data regarding the onset and growth of TTS at
12 higher frequencies where sensitivities are better” (Finneran et al. 2007). Subsequent, data from
13 Finneran and Schlundt (2010) indicate that TTS onset does occur at lower levels and at higher
14 growth rates with exposures of 20 kHz, compared to those at 3 kHz, in bottlenose dolphins, with
15 Finneran and Schlundt (2013) further examining (exposure frequencies ranging from 3 to 80 kHz)
16 the relationship between frequency and growth rates.
17
18

19 **Table B6: Effect of exposure frequency on TTS.**

20

General Trends	Marine Mammal Studies
<u>Threshold Shifts Amount*:</u> <ul style="list-style-type: none"> Hearing loss is frequency-dependent, with higher levels of TTS (or lower TTS onset) recorded in regions of best hearing sensitivity. 	Finneran et al. 2007; Finneran and Schlundt 2010; Finneran and Schlundt 2013
<u>Growth of TTS:</u> <ul style="list-style-type: none"> Growth rates of TTS (dB of TTS/dB of noise) are higher for frequencies where hearing is more sensitive. 	Finneran and Schlundt 2010; Finneran 2011; Finneran and Schlundt 2013
* The implementation of weighting functions quantitatively allow for frequency-specific consideration of thresholds shifts.	

21
22
23 Additionally, for humans, terrestrial mammals, and marine mammals, pure tone or octave-band
24 noise exposure typically results in a maximum thresholds shift one-half to one octave above the
25 upper frequency of sound exposure (often called “half-octave shift,” e.g., Hirsch and Bilger 1955;
26 Cody and Johnstone 1981; Cappaert et al. 2000; Yost 2007; Finneran et al. 2007; Popov et al.
27 2011a; Popov et al. 2011b). Thus, PTS and TTS rarely encompasses an individual’s entire
28 auditory range because the anthropogenic sounds themselves are not broad enough to overlap a
29 marine mammal’s entire hearing range.
30
31

32 **III. MANAGING DATA LIMITATIONS AND UNCERTAINTY**

33
34 NOAA, like Southall et al. (2007) in their scientific recommendations for TTS and PTS onset
35 acoustic threshold levels, acknowledges the inherent data limitations that occur in many
36 instances when assessing acoustic effects on marine mammals. For example, data are typically
37 only available from a limited number of species and within species, a limited number of
38 individuals. Thus, extrapolations had to be made when there were no data available for a hearing
39 group/sound source. Furthermore, Southall et al. (2007) did not provide explicit guidance on how
40 acoustic threshold levels should be created or revised as more data become available (e.g., when
41 is there enough data from an individual species to establish a separate acoustic threshold level).
42 As a result, NOAA developed certain assumptions to address uncertainty when establishing
43 numerical acoustic threshold levels for TTS onset (Table B7).

1
2
3
4

Table B7: NOAA’s Protocol for accounting for uncertainty in establishing TTS onset acoustic threshold levels for marine mammals within a sound source category.

Step 1: Number of Species with Data within Hearing Group	Step 2: Number of Individuals with Data within a Species	Step 3: Hearing Group Representative for Establishing TTS Onset Acoustic threshold Level*	Example Scenarios (A through F)
None	—	Surrogates chosen based on the closest related hearing group	A) Use mid-frequency cetaceans (as opposed to high-frequency) cetaceans as surrogates for low-frequency cetaceans
One	Few (1- 4 individuals)	Individual with lowest threshold for TTS onset	B) Data from 1 beluga: Take the lowest TTS onset acoustic threshold level
	Several (≥ 5 individuals)	Median ⁺ of individuals' lowest thresholds for TTS onset	C) Data from 5 bottlenose dolphins: Take the median of all the individuals' lowest TTS onset acoustic threshold level
Multiple	All species with few (1- 4 individuals)	Most conservative species: Individual with lowest threshold for TTS onset	D) Data from bottlenose dolphin and beluga: Take one with the lowest TTS onset acoustic threshold level
	Species with both few (1- 4 individuals) and Several (≥ 5 individuals)	<u>Whichever is the lowest:</u> 1) Few individuals: Individual with lowest threshold for TTS onset <u>or</u> 2) Several individuals: Median ⁺ of individuals' lowest threshold for TTS onset Median of single species' lowest individual thresholds for TTS onset can also represent that particular species	E) Data from 1 beluga and 5 bottlenose dolphins: Take whichever is the lowest (either the lowest TTS onset threshold for the beluga or the median of all the bottlenose dolphins' lowest TTS thresholds). Bottlenose dolphins could have their own separate data-based acoustic threshold level (i.e., separate from rest of hearing group).
	All species with several (≥ 5 individuals)	Species with the lowest median ⁺ of individuals' lowest thresholds for TTS onset. Median of single species' lowest individual thresholds for TTS onset can also represent that particular species	F) Data from 5 bottlenose dolphins and 5 belugas: Take whichever is the lowest (either the median of all the bottlenose dolphins' lowest TTS thresholds or the median of all the belugas' lowest TTS thresholds). Bottlenose dolphins or beluga could have their own separate data-based acoustic threshold level (i.e., separate from rest of hearing group).

* TTS onset is lowest acoustic threshold level with at least a 6 dB or greater threshold shift. This table also does not make a distinction for different sound sources *within* a sound source category (impulsive or non-impulsive). Although applying appropriate weighting functions in conjunction with the proposed acoustic threshold levels help to account for some frequency-specific effects.

To best reflect scenarios expected to be encountered by wild individuals, only data points with exposure durations of one hour or less are considered in NOAA's analysis.

+ When median thresholds are reported, please also report the data range and 1st and 3rd quartiles.

5
6

1 These assumptions help to ensure that NOAA is assessing data in a consistent manner. The
2 protocols for addressing uncertainty should also be useful as more data become available in the
3 future. Currently, these protocols are based on functional hearing groups, but NOAA
4 acknowledges that as more data become available the relatedness of various genus and/or
5 species within a single family may be an important additional consideration (i.e., specific acoustic
6 threshold levels may be able to be derived by family, genus, and/or species). Furthermore, as
7 more data are collected, NOAA will be better able to identify outliers (e.g., one individual has an
8 unusually high or low threshold or testing procedures led to flawed results) and make necessary
9 adjustments (i.e., removal of an outlier datum).

10
11 NOAA's PTS onset acoustic threshold levels are informed by data from terrestrial mammals and
12 humans (as are the Southall et al. 2007 thresholds) and have been set at levels below predicted
13 PTS onset for most species. As new data become available, these acoustic threshold levels will
14 be adjusted. At this time, NOAA's determination of where appropriate acoustic threshold levels
15 occur is supported by the existing best available science.

16 17 18 **3.1 Representative Species/Individuals**

19
20 Currently, TTS data only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor
21 porpoises, and Yangtze finless porpoise). For bottlenose dolphins, data are available from
22 multiple individuals, while for belugas data comes from four individuals and for harbor porpoises
23 and Yangtze finless porpoises all data come from just two individuals for each species. For
24 pinnipeds, TTS data exist for three species (Northern elephant seal, harbor seal, and California
25 sea lion), but only for a single individual of Northern elephant seal, lone California sea lion
26 (Finneran et al. 2003 tested exposed two California sea lions but could not induce TTS), and
27 three harbor seals.

28
29 Whether these captive individuals are representative (i.e., where this individual's measurements
30 fall within the larger population) of their species, hearing group, and for marine mammals in
31 general (e.g., susceptibility of anthropogenic sound has been shown to vary among terrestrial
32 mammal species; Drescher and Eldredge 1974; Borg and Viberg 1995; Duan et al. 2008;
33 Henderson et al. 2008) is unknown. Nevertheless, these studies contain the only data currently
34 available. NOAA has made assumptions to prevent the interpretation of these data beyond what
35 they truly represent. NOAA recognizes that as more data become available, for a broader array of
36 species and individuals within a species, our acoustic threshold levels will need to be re-
37 examined.

38 39 40 **3.2 Representative Sound Sources**

41
42 For cetaceans, most TTS studies have focused on sound sources (both impulsive and non-
43 impulsive sources) with the majority of their acoustic energy below 10 kHz (Table B8; Finneran et
44 al. 2007). This is often below the best hearing range of the species being tested. For example,
45 non-impulsive sound source TTS studies have primarily focused on exposures with frequencies in
46 the range of tactical mid-frequency active (MFA) sonar (1 to 10 kHz). For pinnipeds underwater,
47 there have been even fewer TTS studies conducted, with even fewer sound sources (Table B8).

1
2
3

Table B8: Sound sources associated with cetacean and underwater pinniped TTS studies.

Sound Source	Predominant Frequency and Exposure Duration	Reference
Cetacean Studies		
Seismic watergun (impulsive)	<u>Frequency:</u> Broadband up to 40 kHz, most energy below 1 kHz <u>Duration:</u> ~6.3 to 73 msec	Finneran et al. 2002
Explosion simulator (impulsive)	<u>Frequency:</u> Broadband up to 40 kHz, most energy between 1-10 kHz <u>Duration:</u> 5.1 to 13 msec	Finneran et al. 2000
Single airgun (impulsive)	<u>Frequency:</u> Broadband up to 20 kHz, most energy below 500 Hz <u>Duration:</u> less than 50 msec	Lucke et al. 2009
Tones (non-impulsive)	<u>Frequency:</u> 0.4, 1.5, 3, 10, 20, or 75 kHz <u>Duration:</u> 1 to 128 s or 60 min	Schlundt et al. 2000; Finneran et al. 2005; Finneran et al. 2007; Finneran et al. 2010a; Finneran et al. 2010b; Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2013c
Octave-band noise (non-impulsive)	<u>Frequency:</u> 4 kHz center, from 4 to 8 kHz or 4 to 11 kHz <u>Duration:</u> 1.875 to 54 min, 60 min, or 120 min	Nachtigall et al. 2003; Nachtigall et al. 2004; Mooney et al. 2009a; Kastelein et al. 2012b
Half octave-band noise (non-impulsive)	<u>Frequency:</u> Centered at 22.5 to 128 kHz <u>Duration:</u> 1 to 30 min	Popov et al. 2011a; Popov et al. 2011b; Popov et al. 2013
Impact pile driving (impulsive)	<u>Frequency:</u> peak 630 Hz, most energy between 0.4 to 5 kHz <u>Duration:</u> 120 min	SEAMARCO 2011
MFA sonar (non-impulsive)	<u>Frequency:</u> Main energy at 3 kHz (higher frequency harmonics) <u>Duration:</u> 3 to 15 s	Mooney et al. 2009b
Underwater Pinniped Studies		
Arc-gap transducer (impulsive)	<u>Frequency:</u> Broadband up to 40 kHz, most energy below 1 kHz <u>Duration:</u> 10.5 to 28.3 msec	Finneran et al. 2003
Impact pile driving (impulsive)	<u>Frequency:</u> peak 630 Hz, most energy between 0.4 to 5 kHz <u>Duration:</u> 120 min	Kastelein et al. 2013a
Octave-band noise (non-impulsive)	<u>Frequency:</u> Centered at 0.1, 0.5, 1, 2, 2.5 kHz, or 4 kHz <u>Duration:</u> 7.5 min, 15 min, 20 min, 22 min, 25 min, 30 min 50 min, 60 min, or 120 min	Kastak et al. 1999; Kastak et al. 2005; Kastelein et al. 2012a; Kastelein et al. 2013b

1 Our current TTS and PTS onset acoustic threshold levels only distinguish between impulsive and
 2 non-impulsive sounds and do not take into account the temporal or spectral characteristics of the
 3 sound source. NOAA acknowledges that these additional factors still need to be considered, even
 4 if only qualitatively at this point.

5
 6 As more data become available for a broader array of sound sources, especially with sound
 7 pressure levels in various species' most sensitive hearing range, NOAA will consider whether to
 8 adjust its acoustic threshold levels. It may be necessary to refine the acoustic threshold levels
 9 based on particular sound sources (e.g., separate acoustic threshold levels for impulsive pile
 10 driving strikes versus seismic airgun shots), duration of exposure (e.g., continuous vs.
 11 intermittent), or frequency ranges of exposure (e.g., low-, mid-, or high-frequency) rather than by
 12 broad sound source categories.

13
 14
 15 **IV. DEVELOPMENT OF TTS AND PTS ONSET ACOUSTIC THRESHOLD**
 16 **LEVELS**

17
 18 For acoustic threshold levels without associated frequency weighting, see Table B2.

19
 20 **4.1 Temporary Threshold Shifts: Non-Impulsive Sources**

21
 22 **4.1.1 Mid-Frequency Cetaceans**

23
 24 ***Numeric Acoustic threshold Level (Table B9; Cell 14 Table B1a)***

25
 26
 27 **Table B9: TTS onset dual acoustic threshold levels for mid-frequency cetaceans**
 28 **exposed to underwater non-impulsive sound sources.**
 29

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	224 dB _{peak}	Finneran et al. 2002
	178 dB SEL _{cum}	Schlundt et al. 2000; Mooney et al. 2009a; Finneran & Schlundt 2010; Finneran et al. 2010a

30
 31
 32 For bottlenose dolphins and belugas, numerous TTS studies have been conducted using non-
 33 impulsive sound sources (more so than for any other sound source). For bottlenose dolphins, at
 34 least nine different individuals have been exposed to anthropogenic sound, with TTS being
 35 induced in seven²² individuals (Table B10). Thus, bottlenose dolphin data provide an opportunity
 36 to examine how TTS onset varies among a group of individuals. The lowest TTS threshold
 37 (assumed to represent onset) for each individual recorded (regardless of sound source; e.g.,
 38 individual may have been exposed to tones at various frequencies) was chosen. The median of
 39 these weighted data is 178 dB SEL_{cum} (1st Quartile: 175.5 dB SEL_{cum}; 3rd Quartile: 181.6 dB
 40 SEL_{cum}; Table B6, Scenario E).

41
 42
 43
 44
 45
 46
 22 It was not possible to distinguish individual TTS data for dolphin NAY from that of dolphin BEN in the Finneran et al. 2005 study. Thus, data for NAY are not presented.

Table B10: TTS onset in bottlenose dolphins exposed to underwater non-impulsive sound sources.

Individual	Study	Sound Source/Exposure Duration(s)	TTS Onset ⁺ (unweighted)
Boris	Mooney et al. 2009a	Octave band noise (4-8 kHz)/7.5, 15, & 30 min	182.5 dB SEL _{cum} [▲] (189.5 dB SEL _{cum})
TOD	Schlundt et al. 2000	75 kHz tone/1 s	179 dB SEL _{cum} (182 dB SEL _{cum})
NEM	Schlundt et al. 2000	3 kHz tone/1 s	177 dB SEL _{cum} (194 dB SEL _{cum})
BEN	Schlundt et al. 2000	10 kHz tone/1 s	189 dB SEL _{cum} (192 dB SEL _{cum})
TYH	Finneran et al. 2010a	3 kHz tone/either 16, 32, or 64 s [^]	175 dB SEL _{cum} (192 dB SEL _{cum} [^])
BLU	Finneran and Schlundt 2010	3 kHz tone/16 s	174 dB SEL _{cum} (191 dB SEL _{cum} [*])
Descriptive Statistics (n=6: Boris, TOD, NEM, BEN, TYH, BLU) Median: 178 dB SEL _{cum} ; 1 st Quartile: 175.5 dB SEL _{cum} ; 3 rd Quartile: 181.6 dB SEL _{cum} Mean: 179.4 dB SEL _{cum} ; Maximum: 189 dB SEL _{cum} ; Minimum 174 dB SEL _{cum}			
▲ Weighting was based on center frequency of octave-band noise. ^ TTS onset estimated from Figure 3a in Finneran et al. 2010. Since onset is estimated, the exact duration of exposure is unknown, but is either 16, 32, or 64 s. * TTS onset determined from best-fit curve (created from experimental data) rather than a direct measurement at this particular SEL _{cum} .			

For the two individual belugas exposed to non-impulsive sound sources, the lowest TTS onset occurred at a weighted level of 178 dB SEL_{cum} (Schlundt et al. 2000; Table B11), which is identical to the median of the bottlenose dolphin data. Thus, NOAA is using bottlenose dolphin data as a surrogate for all species within this hearing group.

Table B11: TTS onset in belugas exposed to underwater non-impulsive sound sources.

Individual	Study	Sound Source/Exposure Duration(s)	TTS Onset (unweighted)
MUK	Schlundt et al. 2000	10 kHz tone/1s	189 dB SEL _{cum} (192 dB SEL _{cum})
NOC	Schlundt et al. 2000	3 kHz tone/1 s	178 dB SEL _{cum} (195 dB SEL _{cum})

An additional TTS study was also completed by Popov et al. (2011b) on a single male beluga exposed half-octave band noise (32 kHz center frequency) for durations of 1, 3, 10, and 30 minutes using a new methodology for a more quick determination of hearing thresholds after acoustic threshold. They reported thresholds shifts of 20 dB or greater at RLs starting at ~178 dB SEL_{cum} (i.e., TTS onset was not determined). In addition to TTS, recovery was also measured. Popov et al. (2011b) found that recovery occurred in two phases, with fast recovery resulting in rapid and drastic decreases in threshold within the first minutes after acoustic threshold and slow recovery occurring longer afterwards (i.e., 10 to 30 minutes).

Popov et al. (2013) completed another study using both a male and female beluga whale exposed to half-octave band noise (11.2, 22.5, 45, and 90 kHz center frequencies) for durations

of 1, 3, 10, and 30 minutes using similar methodology as was used in Popov et al. 2011b. Again, the goal of this study was to examine a variety of factors that contribute to TTS but not necessarily determine TTS onset. Thus, in the majority of trials, TTS was measured at levels much greater than 6 dB (Table B12).

Table B12: Amount of TTS recorded in Popov et al. 2013 for belugas.

Exposure Duration (SEL _{cum})	TTS at 11.2 kHz*	TTS at 22.5 kHz*	TTS at 45 kHz*	TTS at 90 kHz*
Male beluga				
1 min. (183 dB)	15 dB	27.5 dB	12.5 dB	7.5 dB
3 min. (188 dB)	22.5 dB	45 dB	15 dB	8.8 dB
10 min. (193 dB)	37.5 dB	47.5 dB	25 dB	10 dB
30 min. (198 dB)	47.5 dB	55 dB	42.5 dB	23.8 dB
Female beluga				
1 min. (183 dB)	25 dB	37.5 dB	8.8 dB	21.3 dB
3 min. (188 dB)	27.5 dB	57.5 dB	28.8 dB	21.3 dB
10 min. (193 dB)	50 dB	62.5 dB	43.8 dB	31.3 dB
30 min. (198 dB)	---	----	51.3 dB	31.3 dB

* test frequency = +0.5 octaves

Comparing the TTS measured by Popov et al. 2011b and Popov et al. 2013 with the onset reported in Schlundt et al. 2000 (after applying appropriate weighting functions), NOAA considered whether 178 dB SEL_{cum} was an appropriate acoustic threshold levels for TTS onset. There are some methodological differences between the Schlundt et al. 2000 and two Popov studies that should be considered. Specifically, the Schlundt et al. 2000 study behaviorally measured TTS thresholds, and this typically occurred 1 to 3 minutes after exposure to the fatiguing stimuli. Looking at Figure 2(a) in Popov et al. 2011b, one can see the rapid recovery occurring within the first few minutes after noise exposure (~10 dB within first 5 minutes after noise exposure). Additionally, they exposed this animal at 140 dB for durations up to 30 minutes (~172.5 dB SEL_{cum}) and reported threshold shifts that were “insufficient and hardly detectable.” Thus, taking these factors into consideration, threshold shifts reported in Popov et al. 2011b are more in-line with the results from Schlundt et al. 2000. Nevertheless, this highlights how differing methodologies can make direct comparisons among studies difficult and must be carefully considered.

Validity of the Equal Energy Hypothesis (EEH)

Two recent Mooney et al. (2009a, 2009b) studies and the Finneran et al. (2010a) study indicated that the EEH is not always valid, especially when considering exposure duration. In other words, despite the 189 dB SEL_{cum} threshold, TTS is more likely to occur for those exposures, having the same energy, with longer durations compared to those with short durations (e.g., more likely to have a TTS onset with an exposure 174 dB_{rms} for 63 seconds than of an exposure of 192 dB_{rms} for 1 second). All exposures from Mooney et al. (2009a) that recorded TTS onset were at least 1.875 minutes or longer, with longer exposures inducing TTS more frequently (i.e., 5 out of 7 exposures of 7.5 minutes led to TTS; 6 out of 7 exposures of 15 minutes led to TTS; and 4 out of 5 exposures of 30 minutes led to TTS). Finneran et al. (2010a) found that sound pressure level and duration were better predictors of TTS than just SEL_{cum}. They found that using SEL_{cum} could result in an underestimation of TTS in situations of long-duration exposures, while in situations of short-duration exposures SEL_{cum} could result in an overestimation of TTS.

Based on these studies, NOAA recommends using the SEL_{cum} thresholds contained herein. However, NOAA recommends caution especially when applying these thresholds to activities

1 where there is the potential for long-duration exposures (i.e., minutes or hours compared to
 2 seconds). NOAA encourages applicants to report, in addition to the number of exposures
 3 exceeding the SEL_{cum} threshold, the expected exposure histories (i.e., number and duration of
 4 exposures). This allows for a more complete assessment and means of addressing EEH
 5 concerns (e.g., one can exceed a SEL_{cum} threshold in numerous ways with numerous numbers of
 6 exposures or exposure durations), as well as assessing the potential for recovery.

7
 8 **Exposure Frequency and Duration (Table B13)**

9
 10 Of the recent marine mammal TTS studies, most have focused on non-impulsive sources.
 11 Exposures have consisted of a broad range of frequencies (0.4 to 80 kHz) and durations (1 s to
 12 30 min) (Table B13). The peak pressure acoustic threshold level derived for impulsive sources for
 13 MF cetaceans will also be used for non-impulsive sources (see more detailed description below).
 14
 15

16 **Table B13: Relevant studies provided in the context of exposure frequency and**
 17 **duration.**
 18

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Bottlenose dolphin (5); Beluga (2)	Tones	Frequency: 0.4, 3, 10, 20, or 75 kHz Duration: 1 s	Schlundt et al. 2000
Bottlenose dolphin (1)	Octave-band noise	Frequency: 4 to 11 kHz Duration: 41 to 54 min	Nachtigall et al. 2003
Bottlenose dolphin (1)	Octave-band noise	Frequency: 4 to 11 kHz Duration: 30 min	Nachtigall et al. 2004
Bottlenose dolphin (2)	Tones	Frequency: 3 kHz Duration: 1 to 8 s	Finneran et al. 2005
Bottlenose dolphin (1)	Tones	Frequency: 20 kHz Duration: 48* to 64 s	Finneran et al. 2007
Bottlenose dolphin (1)	Octave-band noise	Frequency: 4 to 8 kHz Duration: 1.875 to 30 min	Mooney et al. 2009a
Bottlenose dolphin (1)	MFA sonar	Frequency: Main energy at 3 kHz (higher frequency harmonics) Duration: 3 to 15 s*	Mooney et al. 2009b
Bottlenose dolphin (2)	Tones	Frequency: 3 kHz Duration: 4 to 128 s	Finneran et al. 2010a
Bottlenose dolphin (1)	Tones	Frequency: 3 kHz Duration: 64 s*	Finneran et al. 2010b
Bottlenose dolphin (1)	Tones	Frequency: 3 or 20 kHz Duration: 16 s	Finneran and Schlundt 2010
Beluga (1)	Half-octave band noise	Frequency: 32 kHz ⁺ (center frequency) Duration: 1 to 30 min	Popov et al. 2011b
Bottlenose dolphin (2)	Tones	Frequency: 3 to 80 kHz Duration: 16 s	Finneran and Schlundt 2013
Beluga (2)	Half-octave band noise	Frequency: 11.2, 22.5, 45, and 90 kHz (center frequency) Duration: 1 to 30 min	Popov et al. 2013

* Experiment consisted of intermittent exposures (i.e., three 16 s exposures, separated by 11 and 13 minutes)
 + Exposures at various half-octave exposures, but only data for 32 kHz is directly presented in Popov et al. 2011b

1 **4.1.2 Low-Frequency Cetaceans**

2
3 ***Numeric Exposure Level (Table B14, Cell 12 Table B1a)***

4
5 **Table B14: TTS onset dual acoustic threshold levels for low-frequency cetaceans**
6 **exposed to underwater non-impulsive sound sources.**

7

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	224 dB _{peak}	Surrogate data (Mid-frequency cetaceans)
	178 dB SEL _{cum}	Surrogate data (Mid-frequency cetaceans)

8
9
10 Direct measurements of hearing for LF cetaceans do not exist, let alone measurements of noise-
11 induced threshold shifts for any of these species. Thus, NOAA has decided to use MF cetaceans
12 as surrogates for LF cetaceans, in terms of establishing TTS onset thresholds (i.e., same TTS
13 onset threshold; Table B6, Scenario A). Mysticetes are believed to have poorer overall sensitivity
14 than other cetacean species due to high background noise levels (especially below 1 kHz) in the
15 frequency range where these species are predicted to hear best (Malme et al. 1989; Ketten 1998;
16 Wartzok and Ketten 1999; Clark and Ellison 2004). NOAA acknowledges that this extrapolation
17 may be conservative, but believes is the appropriate alternative based on currently available data.

18
19 This extrapolation is used for all LF cetacean TTS onset thresholds (as well as PTS onset
20 thresholds) and thus, justification is not repeated later within this Appendix. It is important to
21 remember that despite having identical acoustic threshold levels to MF cetaceans, LF cetaceans
22 have a different auditory weighting function.

23
24 ***Exposure Frequency and Duration***

25
26 There are no data on exposure frequency and duration for LF cetaceans exposed to non-
27 impulsive sound sources. Nevertheless, a LF auditory weighting function has been extrapolated
28 using data for potential auditory capabilities based on vocalization ranges (Ketten 1998) and
29 background sound levels (Clark and Ellison 2004).

30
31
32 **4.1.3 High-Frequency Cetaceans**

33 ***Numeric Exposure Level (Table B15, Cell 16 Table B1a)***

34
35
36 **Table B15: TTS onset dual acoustic threshold levels for high-frequency cetaceans**
37 **exposed to underwater non-impulsive sound sources.**

38

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	195 dB _{peak}	Lucke et al. 2009
	160 dB SEL _{cum}	Kastelein et al. 2012b

39
40
41 There have been three published TTS studies (Popov et al. 2011a; Kastelein et al. 2012b;
42 Kastelein et al. 2013c) on HF cetaceans exposed to non-impulsive sounds. The Popov et al.
43 (2011a) study exposed two Yangtze finless porpoise to half-octave band noise, while the

1 Kastelein et al. (2012b) study exposed a single harbor porpoise to octave-band noise. Kastelein
2 et al. (2013c) exposed a single harbor porpoise to a 1.5 kHz tone.

3
4 From Kastelein et al. (2012b), TTS onset²³ occurred at 172 dB SEL_{cum} (unweighted) for exposure
5 to octave-band noise centered at 4 kHz. After applying the appropriate weighting function, this
6 value becomes ~159.7 dB SEL_{cum} (rounded up to 160 dB SEL_{cum}). Thus based on this study, HF
7 cetaceans are thought to have a lower TTS onset compared to MF cetaceans (Table B16).
8

9 In Kastelein et al. (2012b), 6 dB of TTS also occurred with exposure to 163 dB SEL_{cum}
10 (unweighted; after weighting ~151 dB SEL_{cum}) based on a 120-minute exposure duration. This
11 exposure duration exceeds our protocol for data analysis (Table B7) because exposure was
12 greater than one hour and is considered unlikely encountered by wild individuals. Thus, this
13 particular data point was not considered within our analysis.
14
15

16 **Table B16: TTS onset in high-frequency cetaceans exposed to underwater non-**
17 **impulsive sound sources.**
18

Individual (species)	Study	Sound Source/Exposure Duration(s)	TTS Onset (unweighted)
ID no. 02 (harbor porpoise)	Kastelein et al. 2012b	Octave-band noise/60 min	160 dB SEL _{cum} (172 dB SEL _{cum})
ID no. 02 (harbor porpoise)	Kastelein et al. 2013c	Tone/60 min	170 dB SEL _{cum} (190 dB SEL _{cum})

19
20
21 Kastelein et al. (2013c) exposed the same harbor porpoise as Kastelein et al. (2012b) to a 1.5
22 kHz tone for 60 minutes. TTS occurred at 190 dB SEL_{cum} (unweighted). After applying the
23 appropriate weighting function, it becomes 170 dB SEL_{cum}. Thus, this level of TTS is higher than
24 what was derived in Kastelein et al. 2012b (Table B16). However, it should be noted that
25 Kastelein et al. (2013c) reported TTS of 11 and 14 dB (i.e., not onset).

26 The Popov et al. (2011a) study did not derive TTS onset (for either individual). The lowest level
27 (unweighted) of exposure was 162.5 dB SEL during one trial, with several other trials having
28 exposures at 168 dB SEL (Table B17). As with their TTS study on a beluga, Popov et al. 2011a
29 used a rapid threshold-determination procedure, which may make it difficult to directly compare
30 results to other studies (i.e., Popov et al. 2011a “If the threshold measurement procedure were
31 slower, the early phase of the highest TTS would likely have been missed...”). Nevertheless, the
32 weighted threshold from the Kastelein et al. 2012b data is lower than any of the Popov et al.
33 2011a trials and is deemed the most appropriate and representative of TTS onset threshold
34 (SEL_{cum} metric) for all HF cetaceans at this time.
35
36
37
38
39
40
41
42

²³ In this document, TTS onset is defined as a threshold shift of 6 dB above baseline. In their study, Kastelein et al. (2012b) defined “significant TTS” as a >2.5 dB threshold shift above baseline. Thus, NOAA is relying on the 6 dB definition to define TTS onset and not the definition used by Kastelein et al. (2012b).

Table B17: Amount of TTS recorded by Popov et al. 2011a for exposures at unweighted 168 dB SEL and below.*

Individual	Noise Band	Exposure Time	Test Frequency	SEL _{cum} (unweighted)	Amount of TTS
A Bao (♂)	0.5 octave above	1 minute	32 kHz	168 dB SEL _{cum}	~8 dB [▲]
A Bao (♂)	On frequency	1 minute	32 kHz	168 dB SEL _{cum}	~5 dB [▲]
Ying Ying (♀)	On frequency	1 minute	64 kHz	168 dB SEL _{cum}	~7.5 dB [▲]
Ying Ying (♀)	On frequency	1 minute	128 kHz	168 dB SEL _{cum}	~10 dB [▲]
A Bao (♂)	0.5 octave below	1 minute	32 kHz	168 dB SEL _{cum}	~27.5 dB [▲]
Ying Ying (♀)	0.5 octave below	1 minute	64 kHz	168 dB SEL _{cum}	~22.5 dB [▲]
Ying Ying (♀)	0.5 octave below	1 minute	128 kHz	168 dB SEL _{cum}	~17.5 dB [▲]
A Bao (♂)	0.5 octave below	1 minute	45 kHz	163 dB SEL _{cum}	~25 dB [■]
Ying Ying (♀)	1 octave below	1 minute	64 kHz	168 dB SEL _{cum}	~12 dB [▲]
Ying Ying (♀)	1 octave below	1 minute	128 kHz	168 dB SEL _{cum}	~7.5 dB [▲]

* Of the 42 combinations of exposures within Popov et al. 2011a, there are 12 combinations where exposures were at 168 dB SEL and below. Within their publication, Popov et al. 2011a did not provide amounts of TTS recorded for all of these trials.

[▲] Estimated from Figure 7 in Popov et al. 2011a

[■] Estimated from Figure 10 in Popov et al. 2011a

The peak pressure acoustic threshold level derived for impulsive sources for all cetacean functional hearing groups will also be used for non-impulsive sources due to limited available data (see more detailed description below).

Exposure Frequency and Duration

The two studies on HF cetaceans examined effects of frequency and duration of exposure on TTS (Table B18).

Table B18: Relevant studies and provided in the context of exposure frequency and duration.

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Yangtze finless porpoise (2)	Half-octave band noise	Frequency: 22.5 to 128 kHz (center frequency) Duration: 1 to 30 min	Popov et al. 2011a
Harbor porpoise (1)	Octave-band noise	Frequency: centered at 4 kHz Duration: 7.5, 15, 30, 60, or 120 min	Kastelein et al. 2012b
Harbor porpoise (1)	Tone	Frequency: 1.5 kHz Duration: 60 min	Kastelein et al. 2013c

Kastelein et al. 2012b reported that increasing exposure duration was more effective in elevating the amount of TTS compared to increasing the level, once again showing the EEH does not always hold true.

1 Kastelein et al. 2013c found that hearing thresholds in the range that this species echolocates
 2 (i.e., 125 kHz) was not affected by 1.5 kHz tones. Thus, exposure to lower frequency sounds are
 3 highly unlikely to affect this species ability to forage efficiently. However, they caution that there is
 4 nothing known about the ecological significance of sounds below 120 kHz for harbor porpoise
 5 (e.g., lower frequencies could be used to avoid vessels or predators).
 6

7 Popov et al. 2011a found that, in general, the lower the frequency range of exposure (i.e., 32
 8 kHz), the larger the amount of TTS. This result was reported as unexpected since this species is
 9 more sensitive to higher frequencies (i.e., 45 to 139 kHz). It also took longer for these animals to
 10 recover than these lower frequencies. They also reported exposures of higher level and shorter
 11 duration resulted in higher levels of TTS compared to exposures of lower level and longer
 12 duration, which is contrary to what has been found in other studies (e.g., Kastak et al. 2005;
 13 Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein
 14 et al. 2012b). As more information becomes available, this trend can be further examined.
 15

17 4.1.4 Phocid Pinnipeds (Underwater)

18 *Numeric Exposure Level (Table B19, Cell 18 Table B1a)*

21 **Table B19: TTS onset dual acoustic threshold levels for underwater phocid pinnipeds**
 22 **exposed to non-impulsive sound sources.**
 23

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	229 dB _{peak}	Extrapolation based on protocol from Southall et al. 2007
	183 dB SEL _{cum}	Kastak et al. 2005

24
 25
 26 Data are only available from two species (harbor seal, northern elephant seal) from the Kastak et
 27 al. (2005) and one species (harbor seal) from the Kastelein et al. (2012a) and Kastak et al. (2005)
 28 studies (Table B20). From Kastak et al. (2005), TTS onset was determined directly using these
 29 data, as well as fitting the data to an equation by Maslen (1981). For the harbor seal, TTS onset
 30 was determined to be 183 dB SEL_{cum} and for the Northern elephant seal, it was approximated at
 31 204 dB SEL_{cum}. From the Kastelein et al. 2012a study, TTS onset²⁴ was at ~184 SEL_{cum}.
 32
 33

34 **Table B20: TTS onset in phocid pinnipeds exposed to underwater non-impulsive**
 35 **sound sources.**
 36

Individual (species)	Study	Sound Source/Exposure Duration(s)	TTS Onset (unweighted)
Burnyce (Northern elephant seal)	Kastak et al. 2005	Octave-band noise/22, 25, & 50 min	204 dB SEL _{cum}
Sprouts (harbor seal)	Kastak et al. 2005	Octave-band noise/22, 25, & 50 min	183 dB SEL _{cum}
ID no. 01 (harbor seal)	Kastelein et al. 2012a	Octave band noise/60 min	~184 dB SEL _{cum}

²⁴ In this document, TTS onset is defined as a threshold shift of 6 dB above baseline. In their study, Kastelein et al. (2012b) defined "significant TTS" as a >2.5 dB threshold shift above baseline (where TTS onset occurs at ~170 dB SEL_{cum}). NOAA is choosing the 6 dB definition to define TTS onset and not the definition used by Kastelein et al. (2012a).

1 Based on our protocol (Table B7), the species (harbor seal) with the lowest TTS onset threshold
 2 is used to represent TTS onset in all phocid pinniped species exposed to underwater non-
 3 impulsive sound sources. Thus, 183 dB SEL_{cum} is the TTS onset for the entire phocid group.
 4

5 The peak pressure acoustic threshold level derived for impulsive sources for pinnipeds is being
 6 used for non-impulsive sources due to limited available data (see more detailed description
 7 below).
 8

9 In Kastelein et al. (2012a), 8.1 dB of TTS occurred with exposure at ~175 dB SEL_{cum} and 8 dB of
 10 TTS occurred with exposure at ~178 dB SEL_{cum}. The exposure durations associated with both
 11 these threshold shifts were longer than one hour (i.e., 120 and 240 minutes). They are
 12 considered exposure durations unlikely encountered by wild individuals, and thus, the data points
 13 are excluded from further analysis.
 14

15 Kastelein et al. 2013b unintentionally exposed a harbor seal to 60 minutes of octave-band noise
 16 (centered at 4 kHz) at mean levels of 163 dB (SEL_{cum} of ~199 dB). This exposure resulted in TTS
 17 of 44 dB, which took four days for complete recovery. From this study, Kastelein et al. (2013b)
 18 suggested a critical level (i.e., above which TTS increased rapidly with increasing SPLs) between
 19 186 to 196 dB SEL_{cum}. NOAA did not directly apply these critical levels in its updated PTS onset
 20 acoustic threshold level, but it should be noted that our PTS onset level is lower than Kastelein et
 21 al. 2013b, which resulted in complete recovery.
 22
 23

24 **Exposure Duration and Frequency (Table B21)**
 25

26 The four available studies consisted of vary similar exposure frequencies and durations.
 27 However, longer duration exposures (i.e., 50 min) from Kastak et al. (2005) resulted in TTS onset
 28 compared to shorter duration exposures (i.e., 22 to 25 min), with the same trend seen in
 29 Kastelein et al. (2012a) and Kastelein et al. (2013b). However, these longer duration exposures
 30 also resulted in a higher SEL_{cum}. Thus, effects of duration cannot be determined. Kastelein et al.
 31 (2012a) found that duration played a greater factor in the amount of TTS induced compared to
 32 level, which is a similar trend reported in other studies (e.g., Mooney et al. 2009a).
 33
 34

35 **Table B21: Relevant studies and provided in the context of exposure frequency and**
 36 **duration.**
 37

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Harbor seal (1); Northern elephant seal (1)	Octave-band noise	Frequency: Centered at 0.1, 0.5, 1, or 2 kHz Duration: 20 to 22 min	Kastak et al. 1999
Harbor seal (1); Northern elephant seal (1)	Octave-band noise	Frequency: Centered at 2.5 kHz Duration: 22, 25, or 50 min	Kastak et al. 2005
Harbor seal (2)	Octave-band noise	Frequency: centered at 4 kHz Duration: 7.5, 15, 30, 60, 120, or 240 min	Kastelein et al. 2012a; Kastelein et al. 2013b

38
 39
 40
 41
 42

1 **4.1.5 Otariid Pinnipeds (Underwater)**

2
3 ***Numeric Exposure Level (Table B22, Cell 20 Table B1a)***

4
5 **Table B22: TTS onset dual acoustic threshold levels for underwater otariid pinnipeds**
6 **exposed to non-impulsive sound sources.**

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	229 dB _{peak}	Extrapolation from phocid pinnipeds as surrogate
	206 dB SEL _{cum}	Kastak et al. 2005

8
9
10 Data are only available from one individual of one species (i.e., California sea lion) from the
11 Kastak et al. (2005) study. For the California sea lion onset of TTS (206 dB SEL_{cum}) was
12 determined directly using these data, as well as fitting the data to an equation by Maslen (1981).
13 NOAA recommends using 206 dB SEL_{cum} for all otariid pinnipeds.

14
15 The peak pressure acoustic threshold level derived for impulsive sources for pinnipeds will also
16 be used for non-impulsive sources due to limited available data (see more detailed description
17 below).

18
19
20 ***Exposure Duration and Frequency (Table B23)***

21
22 The Kastak et al. (1999) and Kastak et al. (2005) studies consisted of vary similar exposure
23 frequencies and durations. However, longer duration exposures (i.e., 50 min) from Kastak et al.
24 (2005) resulted in more TTS compared to shorter duration exposures (i.e., 22 to 25 min). From
25 these limited data, the effects of duration cannot be determined.

26
27
28 **Table B23: Relevant studies and provided in the context of exposure frequency and**
29 **duration.**

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
California sea lion (1)	Octave-band noise	Frequency: Centered at 0.1, 0.5, 1, or 2 kHz Duration: 20 to 22 min	Kastak et al. 1999
California sea lion (1)	Octave-band noise	Frequency: Centered at 2.5 kHz Duration: 22 to 50 min	Kastak et al. 2005

30
31
32
33 **4.2 Temporary Threshold Shifts: Impulsive Sources**

34
35 **4.2.1 Mid-Frequency and Low-Frequency Cetaceans**

36
37 ***Numeric Exposure Level (Table B24, Cells 11 & 13 Table B1a)***
38

Table B24: TTS onset dual acoustic threshold levels for mid-frequency and low-frequency cetaceans exposed to underwater impulsive sound sources.

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	224 dB _{peak}	Finneran et al. 2002
	172 dB SEL _{cum}	Finneran et al. 2002

Between the two studies on MF cetaceans exposed to an impulsive sound source (Finneran et al. 2000; Finneran et al. 2002), there was only one incidence where TTS above 6 dB was recorded (Finneran et al. 2002). This was for an individual beluga exposed to a single pulse of a seismic watergun at the unweighted level of 186 dB SEL_{cum} and 23.2 dB pounds per square inch (psi; approximately 224 dB_{peak}). When the weighting function for MF cetaceans is applied, the SEL_{cum} acoustic threshold level becomes 172 dB SEL_{cum}.

Since these are the only data that exist for MF cetaceans, NOAA adopts these thresholds as our dual acoustic threshold levels for TTS onset for both LF (since no data exist) and MF cetaceans. Consequently, since the 224 dB_{peak} is the only data point available for the peak pressure metric, it will be used for all cetacean species, except HF cetaceans (see below), and for all sound sources (i.e. impulsive and non-impulsive sounds).

NOAA is aware that studies are currently underway to understand TTS associated with exposure to multiple airgun shots in bottlenose dolphins (SPAWAR study²⁵). These data will be critical in informing future acoustic threshold levels for impulsive sources, once they become available.

Exposure Frequency and Duration (Table B25)

Based upon the two studies available for consideration by NOAA, the band of exposure frequencies was fairly similar, and despite differences in exposure duration, only one incidence resulted in TTS above 6 dB. This was for a beluga exposed to a 6.3 msec seismic watergun pulse.

Table B25: Relevant studies and provided in the context of exposure frequency and duration.

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Bottlenose dolphin (2); Beluga (1)	Explosion simulator	Frequency: Broadband up to 40 kHz (most energy between 1-10 kHz) Duration: 5.1 to 13 msec	Finneran et al. 2000
Bottlenose dolphin (1); Beluga (1)	Seismic watergun	Frequency: Broadband up to 40 kHz (most energy below 1 kHz) Duration: ~6.3 to 73 msec	Finneran et al. 2002

²⁵ <http://www.soundandmarinelife.org/>

1 **4.2.2 High-Frequency Cetaceans**

2
3 **Numeric Exposure Level (Table B26, Cell 15 Table B1a)**

4
5 **Table B26: TTS onset dual acoustic threshold levels for high-frequency cetaceans**
6 **exposed to underwater impulsive sound sources.**

7

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	195 dB _{peak}	Lucke et al. 2009
	146 dB SEL _{cum}	Lucke et al. 2009

8
9
10 Lucke et al. (2009) provided the first TTS study for a HF cetacean (i.e., a single harbor porpoise
11 exposed to single airgun pulses). This study approximates TTS onset to occur at 164.3 dB
12 SEL_{cum} flat-weighted and 199.7 dB_{peak-peak} (dB_{p-p}), which is ~195 dB_{peak} (personal communication
13 Lucke 2009²⁶). Applying HF cetacean weighting functions to these data result in a TTS onset of
14 146 dB SEL_{cum}. SEAMARCO 2011 presented preliminary data for a harbor porpoise exposed to
15 playbacks of impact pile driving²⁷, but at an unweighted level of 158 dB SEL_{cum} (highest level that
16 could be produced without distortion), no TTS was measured.

17
18 Given these limited data, NOAA has decided to recommend 146 dB SEL_{cum} and 195 dB_{peak} as our
19 dual acoustic threshold levels for TTS onset for all members of the HF cetacean hearing group.
20 The 195 dB_{peak} acoustic threshold level is also used as the peak pressure acoustic threshold level
21 for HF cetaceans exposed to non-impulsive sounds.

22
23
24 **Exposure Frequency and Duration (Table B27)**

25
26 Data are limited for one species from two separate studies. Thus, the effects of exposure
27 frequency and duration on TTS cannot not be determined.

28
29
30 **Table B27: Relevant studies and provided in the context of exposure frequency and**
31 **duration.**

32

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Harbor porpoise (1)	Single airgun	Frequency: Broadband up to 20 kHz (most energy below 500 Hz) Duration: Less than 50 msec	Lucke et al. 2009
Harbor porpoise (1)	Impact piled driving	Frequency: peak 630 Hz, most energy between 0.4 to 5 kHz Duration: 120 min	SEAMARCO 2011

33
²⁶ Klaus Lucke, directly, provided the dB_{peak} equivalent for the dB_{peak-peak} threshold, which was not included in Lucke et al. 2009.

²⁷ Playbacks not entirely representative of actual pile strikes.

1 **4.2.3 Phocid Pinnipeds (Underwater)**

2
3 ***Numeric Exposure Level (Table B28; Cell 17 Table B1a)***

4
5 **Table B28: TTS onset dual acoustic threshold levels for underwater phocid pinnipeds**
6 **exposed to impulsive sound sources.**

7

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	229 dB _{peak}	Extrapolation based on protocol from Southall et al. 2007
	177 dB SEL _{cum}	Extrapolation based on protocol from Southall et al. 2007

8
9
10 Few studies examining pinniped TTS after exposure to impulsive sources have been conducted.
11 Preliminary data from Kastelein et al. (2013a) indicate that exposing two harbor seals to impact
12 pile driving recordings²⁸ up to 183 dB SEL_{cum} (unweighted) did not cause measurable TTS.
13 Thus, there are no datasets available to use to derive TTS onset acoustic threshold levels for
14 phocid pinnipeds exposed to impulsive sound sources. When Southall et al. (2007) developed
15 scientific recommendations for marine mammal acoustic threshold levels, they encountered the
16 same situation and derived a means for estimating an exposure level from available datasets.

17
18 Southall et al. 2007's approach assumes the known pinniped-to cetacean difference in TTS-onset
19 upon exposure to non-impulsive sounds would also apply (in a relative sense) to impulsive
20 sounds. Specifically, with non-impulsive sounds, harbor seals experience TTS-onset at
21 approximately 5 dB higher received levels than do bottlenose dolphins (i.e., 183 dB SEL_{cum}
22 versus 178 dB SEL_{cum}). Assuming that this difference for non-impulsive sounds exists for pulses
23 as well, TTS-onset in phocids exposed to single underwater pulses is estimated to occur at a
24 peak pressure of 229 dB_{peak} and/or 177 dB SEL_{cum}. Each of these metrics is 5 dB more than the
25 comparable value for MF cetaceans. The dB SEL_{cum} acoustic threshold level is probably a bit
26 lower than the actual onset because Kastelein et al. (2013a) did not record any incidents of TTS
27 at RL of 183 dB SEL_{cum}. As more data become available, this acoustic threshold level may be
28 modified (i.e., based on actual data versus using a protocol to derive acoustic threshold levels).

29
30
31 ***Exposure Frequency and Duration (Table B29)***

32
33 As mentioned above, there has only been one study exposing phocid pinnipeds to an impulsive
34 source and TTS was not induced. Nevertheless, information on the duration and frequencies
35 associated with these exposures is presented below.

36
37
38 **Table B29: Relevant studies and provided in the context of exposure frequency and**
39 **duration.**

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
Harbor seal (2)	Impact pile driving	Frequency: 630 Hz peak (most energy between 0.4 to 5 kHz) Duration: 120 min	Kastelein et al. 2013a

²⁸ Playbacks are not completely representative of actual pile strikes.

1 **4.2.4 Otariid Pinnipeds (Underwater)**

2
3 ***Numeric Acoustic threshold Level (Table B30; Cell 19 Table B1a)***

4
5 **Table B30: TTS onset dual acoustic threshold levels for underwater otariid pinnipeds**
6 **exposed to impulsive sound sources.**

Effect	Exposure Level (Received Level)	Reference
TTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	229 dB _{peak}	Extrapolation from phocid pinnipeds as surrogate
	200 dB SEL _{cum}	Extrapolation based on protocol from Southall et al. 2007

8
9
10 Finneran et al. (2003) exposed two California sea lions to an arc-gap transducer, and despite
11 exposures with SEL_{cum} as high 163 dB SEL_{cum} (unweighted), TTS was not induced.

12
13 Similar to phocid pinnipeds, there are not enough data to derive directly TTS onset acoustic
14 threshold levels for impulsive sources for otariid pinnipeds. Thus, the same protocol (Southall et
15 al. 2007) was used to derive phocid acoustic threshold levels. This protocol results in a 200 dB
16 SEL_{cum} TTS onset acoustic threshold level for otariid pinnipeds (i.e., 28 dB difference between
17 California sea lion and bottlenose dolphin TTS onset acoustic threshold levels for non-impulsive
18 sound sources).

19
20 If this same protocol were applied to derive the peak pressure acoustic threshold levels, this
21 would result in an unrealistically high onset level (i.e., 252 dB_{peak}). Thus, instead of using the
22 acoustic threshold level derived from the protocol in Southall et al. 2007, NOAA recommends
23 using the peak pressure acoustic threshold level derived for phocid pinnipeds (i.e., 229 dB_{peak})
24 until more data become available.

25
26
27 ***Exposure Frequency and Duration (Table B31)***

28
29 As mentioned above, there has only been one study exposing otariid pinnipeds to an impulsive
30 source, and TTS was not induced. Nevertheless, information on the duration and frequencies
31 associated with these exposures is presented below.

32
33
34 **Table B31: Relevant studies and provided in the context of exposure frequency and**
35 **duration.**

Species (number of individuals)	Sound source	Predominant Frequency and Exposure Duration	Reference
California sea lion (2)	Arc-gap transducer	Frequency: 0.1 to 40 kHz (most energy below 1 kHz) Duration: 10.5 to 28.3 msec	Finneran et al. 2003

37
38
39 **4.3 Permanent Threshold Shifts: Non-Impulsive Sources**

40
41 PTS has only been induced (unintentionally) experimentally in a single marine mammal once (7-
42 10 dB shift over 12 months). However, these data are currently not peer reviewed (i.e., abstract,

(Kastak et al. 2008; memorandum to NMFS, Reichmuth 2008) and cannot be used because they cannot be validated and verified. There are no plans for future PTS studies on marine mammals for ethical reasons. Thus, determining PTS onset in marine mammals can only be produced via extrapolations based on hearing loss growth rates (i.e., rate of how quickly threshold shifts grow in relation to increases in decibel level; expressed in dB of TTS/dB of noise) from limited marine mammal TTS studies and more numerous terrestrial mammal TTS/PTS experiments. Typically, 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).

NOAA acknowledges this is a simplistic approach for estimating PTS onset. However, it should be noted that for many of the proposed PTS onset levels, marine mammals have experimentally been exposed to these levels and yet recovered, often within 24 h or less (e.g., Kastak et al. 2005; Nachtigall et al. 2003; Nachtigall et al. 2004; Finneran et al. 2010a ; Popov et al. 2011; the exception is Finneran et al. 2007 that saw recovery within four days after exposure).

4.3.1 All Cetaceans

Numeric Acoustic threshold Level (Table B32, Cells 2, 4, & 6 Table B1a)

Table B32: PTS onset dual acoustic threshold levels for cetaceans exposed to underwater non-impulsive sound sources.

Effect	Exposure Level (Received Level)	Reference
PTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	Mid-frequency and Low-frequency Cetaceans	
	230 dB _{peak}	6 dB addition to TTS level
	198 dB SEL _{cum}	20 dB addition to TTS level
	High-frequency Cetaceans	
	201 dB _{peak}	6 dB addition to TTS level
	180 dB SEL _{cum}	20 dB addition to TTS level

For cetaceans, there are limited data on noise-induced hearing loss growth rates. Data only exist for the bottlenose dolphin, specifically three individuals exposed to non-impulsive sound sources (Finneran et al. 2005a; Schlundt et al. 2006 cited in Southall et al. 2007; Finneran and Schlundt 2010; Finneran and Schlundt 2013), and for the Yangtze finless porpoise, specifically two individuals exposed to half-octave band noise (Popov et al. 2011a). Growth rates for the bottlenose dolphin varied from 0.4 to 1.0 dB of TTS/dB of noise, while Yangtze finless porpoise had reported growth rates ranging from 0.38 to 0.95 dB of TTS/dB of noise. These limited data are primarily from marine mammal experiments designed to produce only small amounts of TTS. Thus, they are not necessarily appropriate for determining rates for larger thresholds shifts, like those associated with PTS. Finneran et al. (2005) explained that “It was likely that the observed growth rate would increase if larger SEL_{cum} (and thus larger amounts of TTS were employed). Experiments producing larger amounts of TTS are necessary to estimate the growth rate of TTS beyond the range of the TTS amounts experimentally observed.”

Recent studies have provided more data on hearing loss growth rates in bottlenose dolphins and factors that influence growth rates in Yangtze finless porpoise. First, Finneran et al. (2010a) reported a growth rate of 0.7 dB/dB of noise for data from four individuals, one individual

1 experiencing as much as 23 dB of TTS. A second study by Finneran and Schlundt (2010)
2 reported that growth rates were frequency dependent (i.e., for 3 kHz exposures rates varied from
3 0.21 to 0.27 dB of TTS/dB of noise and for 20 kHz exposures the rate was 1.2 dB of TTS/dB of
4 noise). Finneran and Schlundt's most recent study (2013), examined growth rates associated with
5 different frequencies of exposure, with most ranging from 0.2 to 0.5 dB of TTS/dB noise, except
6 at three frequencies with higher growth rates (i.e., 14.1 kHz, 20 kHz with rates ~1 dB of TTS/dB
7 noise and 28.3 kHz with a rate of ~4.5 dB TTS/dB noise). Finally, Popov et al. (2011a) recently
8 reported that growth rates for Yangtze finless porpoise varied depending on duration (0.38-0.58
9 dB of TTS/dB of noise) and overall exposure level (0.92-0.95 dB of TTS/dB of noise). NOAA
10 recommends current cetacean growth rates be considered with caution and have thus relied on
11 better established growth rates from terrestrial mammals for estimating PTS onset levels.
12

13 TTS growth rates data for terrestrial mammals exposed to non-impulsive sound sources are more
14 extensive and include data on larger amounts of TTS. It is assumed that the general mechanisms
15 of the mammalian cochlea should be conserved (i.e., mammalian cochlea is similar) between
16 marine and terrestrial mammals (Wartzok and Ketten, 1999; Ketten 2000). Thus, using terrestrial
17 mammals as surrogates for marine mammals is appropriate. Mills et al. (1979) summarize many
18 of the terrestrial mammal non-impulsive growth rates, which typically vary from 1.4 to 2.0 dB of
19 TTS/dB of noise. Although, consistently, a growth rate between 1.6 and 1.7 dB of TTS/dB of
20 noise has been documented in humans (e.g., Ward et al. 1958; Ward et al. 1959; Melnick 1977;
21 Mills et al. 1979; Mills et al. 1981; Quaranta et al. 1998), chinchillas (e.g., Carder and Miller 1972;
22 Clark 1991), and monkeys (summarized in Mills et al. 1979).
23

24 NOAA has decided to use the well-documented 1.7 dB of TTS/dB of noise growth rate for all
25 cetacean species, in terms of the SEL_{cum} metric, until more marine mammal data become
26 available (same growth rate recommended by Southall et al. 2007). This results in a 20 dB
27 difference between TTS and PTS onset for non-impulsive sources (Table 1A).
28

$$29 \quad 40 \text{ dB TS [PTS onset]} - 6 \text{ dB TS [TTS onset]} / [1.7 \text{ dB of TTS/dB of noise exposure}] = 20 \text{ dB}$$

30

31 NOAA's chosen terrestrial mammal hearing loss growth rates are generally more conservative
32 (i.e., results in PTS onset occurring at a lower SEL_{cum}) than those previously measured in
33 bottlenose dolphins (e.g., marine mammal data would result in a 28 dB+ difference between TTS
34 and PTS, pushing PTS onset to unrealistically high levels). The only marine mammal data that
35 contradicts the terrestrial mammal growth rate data is from Finneran and Schlundt (2013) who
36 recorded a growth rate of ~4.5 dB of TTS/dB noise for a single bottlenose dolphin exposed to a
37 28.3 kHz tone (all other growth rates in this study were 1 dB of TTS/dB of noise or less).
38 Recovery for the animal exposed to this tone was also delayed compared to other frequencies
39 tested. Finneran and Schlundt (2013) attribute these result to exposures possibly exceeding the
40 critical level (i.e., where damage switches from being primarily metabolic to more mechanical) at
41 this frequency. Having data from another individual at this exposure frequency would inform the
42 trend observed in this particular individual. Until that time, NOAA will use the more supported
43 terrestrial mammal growth rate.
44

45 The rationale for establishing growth rates for thresholds expressed in the peak pressure metric
46 are described later and are identical between non-impulsive and impulsive sound sources.
47
48
49
50
51
52
53
54

1 **4.3.2 Underwater Pinnipeds**

2
3 **Numeric Exposure Level (Table B33; Cells 8 & 10 Table B1a)**

4
5
6 **Table B33: PTS onset dual acoustic threshold levels for underwater pinnipeds**
7 **exposed to non-impulsive sound sources.**

8

Effect	Exposure Level (Received Level)	Reference
PTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	Phocid Pinnipeds	
	235 dB _{peak}	6 dB addition to TTS level
	197 dB SEL _{cum}	14 dB addition to TTS level
	Otariid Pinnipeds	
	235 dB _{peak}	Extrapolation from phocid pinnipeds as surrogate
	220 dB SEL _{cum}	14 dB addition to TTS level

9
10
11 The current pinniped noise-induced hearing loss growth rate data are limited to a single California
12 sea lion exposed to a non-impulsive aerial anthropogenic sound source. Kastak et al. (2007)
13 reported a growth rate of 2.5 dB of TTS/dB of noise (maximum mean TTS of 23.5 dB) and
14 indicated, "Because of more efficient testing procedures in air, we believe that aerial data can be
15 used as an alternative for predicting the effects of underwater exposure."

16
17 NOAA has decided to adopt this more conservative hearing loss growth rate (results in 6 dB
18 lower TTS onset acoustic threshold level) for all pinnipeds underwater, as opposed to relying on
19 the well-established terrestrial mammal growth rate used for cetacean growth rates (see previous
20 section). Using the pinniped growth rate results in a 13.6 dB (round it up to 14 dB) difference
21 between TTS and PTS onset (Table 1a):

22
23
$$40 \text{ dB TS [PTS onset]} - 6 \text{ dB TS [TTS onset]} / [2.5 \text{ dB of TTS/dB of noise exposure}] = 13.6 \text{ dB}$$

24
25 The rationale for establishing hearing loss growth rates for acoustic threshold levels expressed in
26 the peak pressure metric are described later and are identical between non-impulsive and
27 impulsive sound sources.

1 **4.4 Permanent Threshold Shifts: Impulsive Sources**

2
3 **4.4.1 All Cetaceans and Underwater Pinnipeds**

4
5 **Numeric Exposure Level (Table B34; Cells 1, 3, 5, 7, & 9 Table B1a)**

6
7
8 **Table B34: PTS onset dual acoustic threshold levels for cetaceans and pinnipeds**
9 **exposed to underwater impulsive sound sources.**

10

Effect	Exposure Level (Received Level)	Reference
PTS onset (Dual acoustic threshold levels: use whichever [dB _{peak} or dB SEL _{cum}] exceeded first)	Mid-frequency and Low-frequency Cetaceans	
	230 dB _{peak}	6 dB addition to TTS level
	187 dB SEL _{cum}	15 dB addition to TTS level
	High-frequency Cetaceans	
	201 dB _{peak}	6 dB addition to TTS level
	161 dB SEL _{cum}	15 dB addition to TTS level
	Phocid Pinnipeds	
	235 dB _{peak}	6 dB addition to TTS level
	192 dB SEL _{cum}	15 dB addition to TTS level
	Otariid Pinnipeds	
	235 dB _{peak}	Extrapolation from phocid pinnipeds as surrogate
	215 dB SEL _{cum}	15 dB addition to TTS level

11
12
13 Data indicate noise-induced hearing loss growth rates associated with impulsive sources are
14 more variable than for non-impulsive sources and can often depend on whether exposure is
15 above or below a “critical level.” From terrestrial mammal studies, there seems to be a critical
16 level where hearing losses shift from a strictly metabolic to a more mechanical mechanism
17 (Henderson et al. 1994; Henderson et al. 2008). Below the critical level, risk of hearing loss is
18 generally more related to total energy of exposure (i.e., EEH), while above the critical level, risk
19 seems more associated with peak pressure (Clark 1991; Henderson et al. 1990; Humes et al.
20 2005). Critical level is not a fixed quantity and can vary by species, along with sound source
21 characteristics and exposure parameters (Price 1981; Roberto et al. 1985; Henderson et al. 1994;
22 Harding and Bohne 2004; Henderson et al. 2008). It also is not limited to just impulsive sounds
23 (i.e., extremely high levels of exposure from either impulsive or non-impulsive sounds can create
24 mechanical fatigue), which has recently been demonstrated in Finneran and Schlundt (2013) that
25 found an unusually high growth rate for exposure to a tone at 28.3 kHz. Nevertheless, it
26 demonstrates that predicting hearing loss is complicated.

27
28 For impulsive sources, Southall et al. (2007) recommended a growth rate of 2.3 dB of TTS/dB of
29 noise. This rate was somewhere in between previously recorded rates below (range from 0.7 to
30 1.9 dB of TTS/dB of noise) and above (range from 2.6 to 7 dB of TTS/dB of noise) the critical
31 levels for terrestrial mammals (Henderson and Hamernik 1982; Henderson and Hamernik 1986;
32 Price and Wansack 1989; Levine et al. 1998; Henderson et al. 2008). Southall et al.’s (2007)

1 recommendation resulted in a more conservative acoustic threshold level for PTS onset than
2 choosing a growth rate below the critical level based on terrestrial data. Thus, NOAA accepts the
3 recommendation made by Southall et al. (2007) as guidance for determining PTS onset for
4 impulsive signals for all cetacean and underwater pinniped species, resulting in an approximate
5 15 dB difference between TTS and PTS onset (Table 1a):

$$6 \quad 40 \text{ dB TS [PTS onset]} - 6 \text{ dB TS [TTS onset]} / [2.3 \text{ dB of TTS/dB of noise exposure}] = 15 \text{ dB}$$

8
9 For the peak pressure acoustic threshold level, Southall et al. (2007) recommended a 6 dB of
10 TTS/dB of noise growth rate. This recommendation was based on several factors, including
11 ensuring that the peak pressure acoustic threshold level did not unrealistically exceed the
12 cavitation of water. Using the rationale of Southall et al. (2007), as well as data for hearing loss
13 growth rates above the critical level for terrestrial mammals, NOAA adopts this hearing loss
14 growth rate for determining PTS onset for all cetaceans and underwater pinnipeds and for all
15 sound sources, including non-impulsive sources that could periodically contain a transient
16 component. This growth rate results in a 6 dB difference between TTS and PTS onset (Table 1a):

$$17 \quad 40 \text{ dB TS [PTS onset]} - 6 \text{ dB TS [TTS onset]} / [6 \text{ dB of TTS/dB of noise exposure}] = 6 \text{ dB}$$

1 **APPENDIX C: PEER REVIEW PROCESS**

2
3
4 **I. PEER REVIEW PROCESS**

5
6 The Office Management and Budget (OMB 2005) states “Peer review is one of the important
7 procedures used to ensure that the quality of published information meets the standards of the
8 scientific and technical community. It is a form of deliberation involving an exchange of judgments
9 about the appropriateness of methods and the strength of the author’s inferences. Peer review
10 involves the review of a draft product for quality by specialists in the field who were not involved in
11 producing the draft.”

12
13 The peer review of this document was conducted in accordance with NOAA’s Information Quality
14 Guidelines²⁹ (IQG), which were designed for “ensuring and maximizing the quality, objectivity,
15 utility, and integrity of information disseminated by the agency” (with each of these terms defined
16 within the IQG). Furthermore, the IQG stipulate that “To the degree that the agency action is
17 based on science, NOAA will use (a) the best available science and supporting studies (including
18 peer-reviewed science and supporting studies when available), conducted in accordance with
19 sound and objective scientific practices, and (b) data collected by accepted methods or best
20 available methods.” Under the IQG and in consistent with OMB’s Final Information Quality
21 Bulletin for Peer Review (OMB Peer Review Bulletin (OMB 2005), our document was considered
22 a Highly Influential Scientific Assessments (HISA)³⁰, and peer review was required before it
23 could be disseminated by the Federal Government.

24
25 OMB (2005) notes “Peer review should not be confused with public comment and other
26 stakeholder processes. The selection of participants in a peer review is based on expertise, with
27 due consideration of independence and conflict of interest.” For the peer review of this document,
28 potential qualified peer reviewers were nominated by a steering committee put together by the
29 Marine Mammal Commission (MMC). The steering committee consisted of MMC Commissioners
30 and members of the Committee of Scientific Advisors (Dr. Daryl Boness, Dr. Douglas Wartzok,
31 and Dr. Sue Moore).

32
33 Nominated peer reviewers were those with expertise marine mammalogy, acoustics/bioacoustics,
34 and/or acoustics in the marine environment. Of the ten nominated reviewers, four were selected
35 as peer reviewers to complete an individual review of the document based on area of expertise
36 and availability (Table D1). The focus of the peer review was on the scientific and technical
37 studies that have been applied and the manner that they have been applied in this document.

38
39 **Table C1: Peer review panel.**

40

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

41
42 The following website contains updated information on the peer review process including: the
43 charge to peer reviewers, peer reviewers’ names, peer reviewers’ individual reports, and NOAA’s
44 response to peer reviewer reports <http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm>

²⁹ http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html

³⁰ “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).

APPENDIX D: GLOSSARY

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

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

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

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

Audible: Heard or capable of being heard.

Audiogram: A graph depicting hearing threshold level as a function of frequency (ANSI 1995; Yost 2007) (Figure D1).

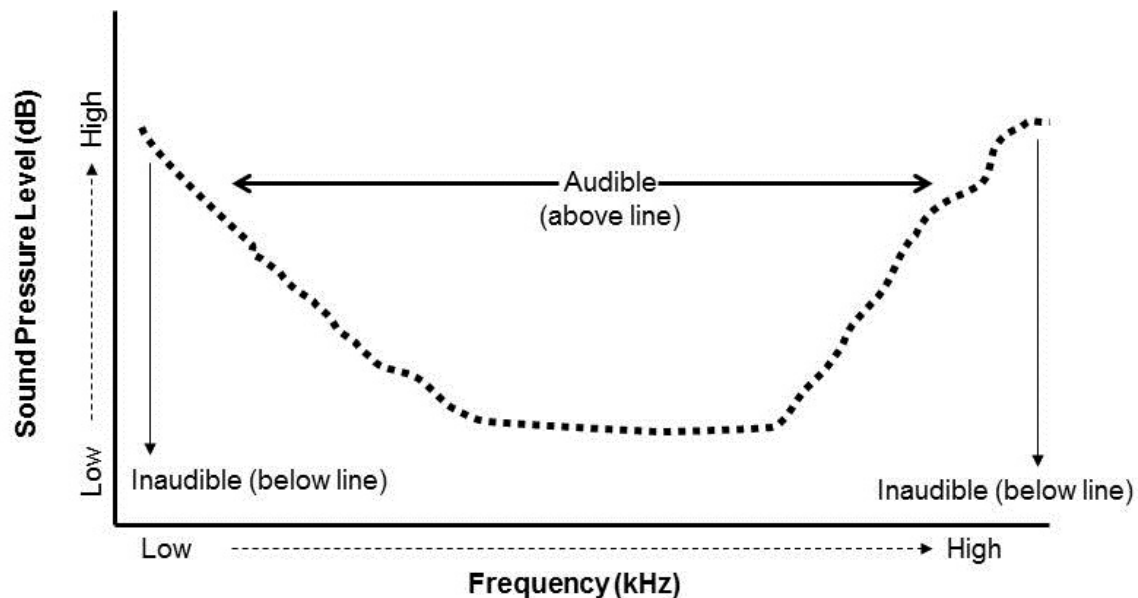


Figure D1. Audiogram.

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

Auditory weighting function (frequency-weighting function): Auditory weighting functions take into account what is known about marine mammal hearing sensitivity and can be applied to a sound-level measurement to account for frequency-dependent hearing (i.e., an expression of relative loudness as perceived by the ear) (Southall et al. 2007; Finneran and Jenkins 2012) (see Figures 1-3).

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 1994).

1 **Bandwidth:** Bandwidth (Hz or kHz) is the range of frequencies over which a sound occurs (ANSI
2 2005). Broadband refers to a source that produces sound over a broad range of frequencies (for
3 example, seismic airguns), while narrowband or tonal sources produce sounds over a narrow
4 frequency range (for example, sonar) (ANSI 2005).

5
6 **Broadband:** See “bandwidth”.

7
8 **Cetacean:** Any number of the order Cetacea of aquatic, mostly marine mammals that includes
9 whales, dolphins, porpoises, and related forms; among other attributes they have a long tail that
10 ends in two transverse flukes (Perrin et al. 2009).

11
12 **Cochlea:** Spirally coiled, tapered cavity within the temporal bone, which contains the receptor
13 organs essential to hearing (ANSI 1995). For cetaceans, based on cochlear measurements two
14 cochlea types have been described for echolocating odontocetes (type I and II) and one cochlea
15 type for mysticetes (type M). Cochlea type I is found in species like the harbor porpoise and
16 Amazon river dolphin, which produce high-frequency echolocation signals. Cochlea type II is
17 found in species producing lower frequency echolocation signals (Ketten 1992).

18
19 **Cognition:** Cognition is all stages of information processing from reception by sensory organs to
20 decisions executed by the brain (Dukas 2004).

21
22 **Continuous sound:** A sound whose sound pressure level remains above ambient sound during
23 the observation period (ANSI 2005).

24
25 **Critical level:** The level at which damage switches from being primarily metabolic to more
26 mechanical; e.g., short duration of impulse can be less than the ear’s integration time, leading for
27 the potential to damage beyond level the ear can perceive (Akay 1978).

28
29 **Cumulative sound exposure level (SEL_{cum}):** Level of acoustic energy accumulated over a given
30 period of time or event (EPA 1982) or specifically, ten times the logarithm to the base ten of the
31 ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a
32 stated time interval or event to the squared reference pressure (ANSI 1994, 1995).

33
34 **Deafness:** A condition caused by a hearing loss that results in the inability to use auditory
35 information effectively for communication or other daily activities (ANSI 1995).

36
37 **Decibel (dB):** One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of
38 ten, and the quantities concerned are proportional to power (ANSI 1994).

39
40 **Endangered Species Act (ESA):** The [Endangered Species Act of 1973 \(ESA\)](#) (16. U.S.C 1531
41 et. seq.) provides for the conservation of [species that are endangered or threatened](#) throughout
42 all or a significant portion of their range, and the conservation of the ecosystems on which they
43 depend.
44 NOAA’s National Marine Fisheries Service and the [U.S. Fish and Wildlife Service \(USFWS\)](#) share
45 responsibility for implementing the ESA.

46
47 **Equal Energy Hypothesis (EEH):** Assumption that sounds of equal energy produce the equal
48 risk for hearing loss (i.e., if the cumulative energy of two sources are similar, a sound from a
49 lower level source with a longer exposure duration may have similar risks to a shorter duration
50 exposure from a higher level source) (Henderson et al. 1991).

51
52 **Equal-loudness contour:** A curve or curves that show, as a function of frequency, the sound
53 pressure level required to cause a given loudness for a listener having normal hearing, listening
54 to a specified kind of sound in a specified manner (ANSI 1994).

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

3
4 **Functional hearing range:** “Functional” refers to the range of frequencies a group hears without
5 incorporating nonacoustic mechanisms (e.g., bone conduction; Wartzok and Ketten 1999).
6 Southall et al. 2007 defined upper and lower limits of the functional hearing range as ~80 dB
7 above most sensitive range. The guidance separates marine mammals under NMFS jurisdiction
8 into five functional hearing groups: low-frequency cetacean, mid-frequency cetacean, high-
9 frequency cetacean, and phocid and otariid pinnipeds.

10
11 **Harmonic:** A sinusoidal quantity that has a frequency which is an integral multiple of the
12 frequency of the periodic quantity to which it is related (ANSI 1994).

13
14 **Hearing loss growth rates:** The rate of threshold shift increase (or growth) as decibel level or
15 exposure duration increase (expressed in dB of temporary threshold shift/dB of noise). Growth
16 rates of threshold shifts are higher for frequencies where hearing is more sensitive (Finneran and
17 Schlundt 2010; Finneran 2011). Typically, the magnitude of a threshold shift increases with
18 increasing duration or level of exposure, until it becomes asymptotic (growth rate begins to level
19 or the upper limit of TTS; Mills et al. 1979; Clark et al. 1987; Laroche et al. 1989; Yost 2007).

20
21 **Hertz (Hz):** Unit of frequency corresponding to the number of cycles per second. One Hertz
22 corresponds to one cycle per second.

23
24 **High-frequency cetacean:** See “functional hearing group”.

25
26 **Impulsive sound:** Sound sources that are typically transient, brief (less than 1 second),
27 broadband, and consist of high peak pressure with rapid rise time and rapid decay (ANSI 1986;
28 NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event.

29
30 **Information Quality Guidelines (IQG):** Section 515 of the Treasury and General Government
31 Appropriations Act for Fiscal Year 2001 (Public Law 106-554), directs the Office of Management
32 and Budget (OMB) to issue government-wide guidelines ([OMB Guidelines](#)) that “provide policy
33 and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity,
34 utility, and integrity of information (including statistical information) disseminated by federal
35 agencies.” OMB issued guidelines directing each federal agency to issue its own guidelines.
36 NOAA’s Information Quality Guidelines can be viewed at:
37 http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html

38
39 **Integration time (of the ear):** In order for a signal to be detected by the ear it must have some
40 critical amount of energy. The process of summing the power to generate the required energy is
41 completed over a particular integration time. If the duration of a signal is less than the integration
42 time required for detection, the power of the signal must be increased in order for it to be detected
43 by the ear (Yost 2007).

44
45 **Intermittent sound:** Interrupted levels of low or no sound (NIOSH 1998) or bursts of sounds
46 separated by silent periods (Richardson and Malme 1993). Typically, intermittent sounds have a
47 more regular (predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle).

48
49 **Low-frequency cetacean:** See “functional hearing group”.

50
51 **Marine Mammal Protection Act (MMPA):** The [Marine Mammal Protection Act \(MMPA\)](#) (16
52 U.S.C. 1361 et. seq.) was enacted on October 21, 1972 and MMPA prohibits, with certain
53 exceptions, the “take” of marine mammals in U.S. waters and by U.S. citizens on the high seas,
54 and the importation of marine mammals and marine mammal products into the United States.
55 NOAA’s National Marine Fisheries Service and the [U.S. Fish and Wildlife Service \(USFWS\)](#) share
56 responsibility for implementing the MMPA.

1
2 **Masking:** Obscuring of sounds of interest by interfering sounds, generally of the similar
3 frequencies (Richardson et al. 1995).

4
5 **Mid-frequency cetacean:** See “functional hearing group”.

6
7 **Mysticete:** The toothless or baleen (whalebone) whales, including the rorquals, gray whale, and
8 right whale; the suborder of whales that includes those that bulk feed and cannot echolocate
9 (Perrin et al. 2009).

10
11 **Narrowband (NB):** See “bandwidth”.

12
13 **National Marine Sanctuaries Act (NMSA):** The [National Marine Sanctuaries Act](#) (16 U.S.C.
14 1431 et. seq.) authorizes the Secretary of Commerce to designate and protect areas of the
15 marine environment with special national significance due to their conservation, recreational,
16 ecological, historical, scientific, cultural, archeological, educational, or esthetic qualities as
17 national marine sanctuaries. Day-to-day management of national marine sanctuaries has been
18 delegated by the Secretary of Commerce to NOAA’s Office of National Marine Sanctuaries.

19
20 **National Standard 2 (NS2):** The [Magnuson-Stevens Fishery Conservation and Management Act](#)
21 [\(MSA\)](#) (16 U.S.C. 1801 et. seq.) is the principal law governing marine fisheries in the U.S. and
22 includes [ten National Standards](#) to guide fishery conservation and management. One of these
23 standards, referred to as [National Standard 2 \(NS2\)](#), guides scientific integrity and states that
24 “(fishery) conservation and management measures shall be based upon the best scientific
25 information available.”

26
27 **Non-impulsive sound:** Sound sources that are broadband, narrowband or tonal, brief or
28 prolonged, continuous or intermittent, and typically do not have a high peak pressure with rapid
29 rise time (typically only small fluctuations in decibel level) that impulsive signals do (ANSI 1995;
30 NIOSH 1998). Examples of non-impulsive sound sources include: marine vessels, aircraft,
31 machinery operations/construction, certain active sonar (e.g. tactical), and vibratory pile driving.

32
33 **Octave:** The interval between two sounds having a basic frequency ratio of two (Yost 2007). For
34 example, one octave above 400 Hz is 800 Hz. One octave below 400 Hz is 200 Hz.

35
36 **Odontocete:** The toothed whales, including sperm and killer whales, belugas, narwhals, dolphins
37 and porpoises; the suborder of whales including those able to echolocate (Perrin et al. 2009).

38
39 **Otariid:** The eared seals (sea lions and fur seals), which use their foreflippers for propulsion
40 (Perrin et al. 2009).

41
42 **Peak-to-peak sound pressure level (dB_{p-p}; re: 1 μPa):** The absolute difference between the
43 maximum and minimum values of the instantaneous sound pressure (ANSI 1994).

44
45 **Peak pressure sound pressure level (dB_{peak}; re: 1 μPa):** The greatest absolute instantaneous
46 sound pressure within a specified time interval (ANSI 1986; ANSI 1994).

47
48 **Perception:** Perception is the translation of environmental signals to neuronal representations
49 (Dukas 2004).

50
51 **Permanent threshold shift (PTS):** A permanent, irreversible increase in the threshold of
52 audibility at a specified frequency or portion of an individual’s hearing range above a previously
53 established reference level. The amount of permanent threshold shift is customarily expressed in
54 decibels (ANSI 1995; Yost 2007). Available data from humans and other terrestrial mammals
55 indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward
56 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

1
2 **Phocid:** A family group within the pinnipeds that includes all of the “true” seals (i.e. the “earless”
3 species). Generally used to refer to all recent pinnipeds that are more closely related to *Phoca*
4 than to otariids or the walrus (Perrin et al. 2009).
5
6 **Pinniped:** Seals, sea lions and fur seals (Perrin et al. 2009).
7
8 **Received Level (RL):** The level of sound measured at the receiver.
9
10 **Reference pressure:** See sound pressure level.
11
12 **Rise time:** The time interval a signal takes to rise from 10% to 90% of its highest peak (ANSI
13 1986; ANSI 1994).
14
15 **Root-mean-square sound pressure level (dB_{rms}; re: 1 μPa):** The square root of the average of
16 the square of the pressure of the sound signal over a given duration (ANSI 1986; ANSI 1994).
17
18 **Sensation level (dB):** The pressure level of a sound above the hearing threshold for an
19 individual or group of individuals (ANSI 1995; Yost 2007).
20
21 **Sound Exposure Level (SEL):** A measure of sound level that takes into account the duration of
22 the signal. Ten times the logarithm to the base 10 of the ratio of a given time integral of squared
23 instantaneous frequency-weighted sound pressure over a stated time interval or event to the
24 product of the squared reference sound pressure (1 μPa in water) and reference duration of one
25 second (ANSI 1994).
26
27 **Sound Pressure Level (SPL):** A measure of sound level that represents only the pressure
28 component of sound. Ten times the logarithm to the base 10 of the ratio of time-mean-square
29 pressure of a sound in a stated frequency band to the square of the reference pressure (1 μPa in
30 water). Note that a sound pressure level with reference to a pressure of 1 μPa in water in
31 numerically ≈ 26 decibels greater than the sound pressure level for the same sound pressure with
32 a reference to 20 μPa (reference pressure in gasses) (ANSI 1994).
33
34 **Source Level (SL):** The level of a sound measured at a standard reference distance (1 meter)
35 away from the source (Richardson et al. 1995).
36
37 **Spatial:** Of or relating to space or area.
38
39 **Spectral/spectrum:** Of or relating to frequency component(s) of sound. The spectrum of a
40 function of time is a description of its resolution into components (frequency, amplitude, etc.). The
41 spectrum level of a signal at a particular frequency is the level of that part of the signal contained
42 within a band of unit width and centered at a particular frequency (Yost 2007).
43
44 **Temporal:** Of or relating to time.
45
46 **Temporary threshold shift (TTS):** A temporary, reversible increase in the threshold of audibility
47 at a specified frequency or portion of an individual’s hearing range above a previously established
48 reference level. The amount of temporary threshold shift is customarily expressed in decibels
49 (ANSI 1995, Yost 2007). Based on data from cetacean TTS studies (see Southall et al. 2007 for a
50 review), a TTS of 6 dB is considered the minimum threshold shift clearly larger than any day-to-
51 day or session-to-session variation in a subject’s normal hearing ability (Schlundt et al. 2000;
52 Finneran et al. 2000; Finneran et al. 2002).
53
54 **Threshold (of audibility):** The threshold of audibility (auditory threshold) for a specified signal is
55 the minimum effective sound pressure level of the signal that is capable of evoking an auditory
56 sensation in a specified fraction of trials (either physiological or behavioral) (Yost 2007).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56

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 1994).

Transmission (or propagation) loss: Reduction in magnitude of some characteristic of a signal between two stated points in a transmission system (for example the reduction in the magnitude of a signal between a source and a receiver) (ANSI 1994).

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).

LITERATURE CITED

- 1
2
3
4 Ahroon, W.A., R.P. Hamernik, and S.-F., Lei. 1996. The effects of reverberant blast waves on the
5 auditory system. *Journal of the Acoustical Society of America* 100:2247-2257.
6
7 Akay, A. 1978. A review of impact noise. *Journal of the Acoustical Society of America* 64:977-
8 987.
9
10 ANSI (American National Standards Institute). 1986. *Methods of Measurement for Impulse Noise*
11 (ANSI S12.7-1986). New York: Acoustical Society of America.
12
13 ANSI (American National Standards Institute). 1994. *Acoustic Terminology* (ANSI S1.1-1994).
14 New York: Acoustical Society of America.
15
16 ANSI (American National Standards Institute). 1995. *Bioacoustical Terminology* (ANSI S3.20-
17 1995). New York: Acoustical Society of America.
18
19 ANSI (American National Standards Institute). 2005. *Measurement of Sound Pressure Levels in*
20 *Air* (ANSI S1.13-2005). New York: Acoustical Society of America.
21
22 Au, W.W.L., and M.C. Hastings. 2008. *Principles of Marine Bioacoustics*. New York: Springer.
23
24 Au, W.W.L., A.A. Pack, M.O. Lammers, L.M. Herman, M.H. Deakos, and K. Andrews. 2006.
25 Acoustic properties of humpback whale songs. *Journal of the Acoustical Society of*
26 *America* 120:1103-1110.
27
28 Barber, J.R., K.R. Crooks, K.M. Fristrup. 2010. The costs of chronic noise exposure for terrestrial
29 organisms. *Trends in Ecology and Evolution* 25:180-189.
30
31 Beale, C.M. 2007. The behavioral ecology of disturbance responses. *International Journal of*
32 *Comparative Psychology* 20:111-120.
33
34 Bogen, K.T., and R.C. Spear. 1987. Integrating uncertainty and interindividual variability in
35 environmental risk assessment. *Risk Analysis* 7:427-436.
36
37 Borg, E., and A. Viberg. 1995. Extra inner hair cells: Prevalence and noise susceptibility. *Hearing*
38 *Research* 83:175-182.
39
40 Buck, K., A. Dancer, and R. Franke. 1984. Effect of the temporal pattern of a given noise dose on
41 TTS in guinea pigs. *Journal of the Acoustical Society of America* 76:1090-1097.
42
43 Cappaert, N.L.M., S.F.L. Klis, H. Muijser, B.M. Kulig, and G.F. Smoorenberg. 2000. Noise-
44 induced hearing loss in rats. *Noise & Health* 3:23-32.
45
46 Carder, H.M., and J.D. Miller. 1972. Temporary threshold shifts from prolonged exposure to
47 noise. *Journal of Speech and Hearing Research* 15:603-623.
48
49 Clark, W.W. 1991. Recent studies of temporary threshold shift (TTS) and permanent threshold
50 shift (PTS) in animals. *Journal of the Acoustical Society of America* 90:155-163.
51
52 Clark, C.W., and W.T. Ellison. 2004. Potential use of low-frequency sound by baleen whales for
53 probing the environment: Evidence from models and empirical measurements. Pages
54 564-581 in J.A. Thomas, C.F. Moss, and M. Vater, eds. *Echolocation in Bats and*
55 *Dolphins*. Chicago: University of Chicago Press.
56

1 Clark, W.W., B.A. Bohne, and F.A. Boettcher. 1987. Effect of periodic rest on hearing loss and
2 cochlear damage following exposure to noise. *Journal of the Acoustical Society of*
3 *America* 82:1253-1264.
4

5 Cody, A.R., and B.M. Johnstone. 1981. Acoustic trauma: Single neuron basis for the "half-octave
6 shift." *Journal of the Acoustical Society of America* 70:707-711.
7

8 Cohen, J.T., M.A. Lampson, and T.S. Bowers. 1996. The use of two-stage Monte Carlo
9 simulation techniques to characterize variability and uncertainty in risk analysis. *Human*
10 *and Ecological Assessment* 2:939-971.
11

12 Dahlheim, M.E., and D.K. Ljungblad. 1990. Preliminary hearing study on gray whales
13 (*Eschrichtius robustus*) in the field. Pages 335-346 in J. Thomas and R. Kastelein, eds.
14 *Sensory Abilities of Cetaceans*. New York: Plenum Press.
15

16 Danielson, R., D. Henderson, M.A. Gratton, L. Bianchai, and R. Salvi. 1991. The importance of
17 "temporal pattern" in traumatic impulse noise exposures *Journal of the Acoustical Society*
18 *of America* 90:209-218.
19

20 DeRuiter, S.L., B.L. Southall, J. Calambokidis, W.M.X. Zimmer, D. Sadykova, E.A. Falcones, A.
21 Friedlaender, J.E. Joseph, D. Moretti, G.S. Schorr, L. Thomas, and P.L. Tyack. 2013.
22 First direct measurements of behavioural responses by Cuvier's beaked whales to mid-
23 frequency active sonar. *Biology Letters* 9: published online.
24

25 DOD (Department of Defense). 2004. Department of Defense Instruction: DOD Hearing
26 Conservation Program (HCP). Washington, D.C.: Department of Defense.
27

28 Drescher, D.G., and D.H. Eldredge. 1974. Species differences in cochlear fatigue related to
29 acoustics of outer and middle ears of guinea pig and chinchilla. *Journal of the Acoustical*
30 *Society of America* 56:929-934.
31

32 Duan, M., G. Laurell, J. Qiu, and E. Borg. 2008. Susceptibility to impulse noise trauma in different
33 species: guinea pig, rat and mouse. *Acta Oto-Laryngologica* 128:277-283.
34

35 Dukas, R. 2004. Causes and consequences of limited attention. *Brain, Behavior and Evolution*
36 63:197-210.
37

38 Ellison, W.T., B.L. Southall, C.W. Clark, and A.S. Frankel 2012. A new context-based approach to
39 assess marine mammal behavioral responses to anthropogenic sounds. *Conservation*
40 *Biology* 26:21-28.
41

42 EPA (Environmental Protection Agency). 1982. Guidelines for Noise Impact Analysis (EPA
43 Report Number 550/9-82-105). Washington, D.C.: Office of Noise Abatement and
44 Control.
45

46 Finneran, J.J. 2011. Auditory weighting functions and frequency-dependent effects of sound in
47 bottlenose dolphins (*Tursiops truncatus*). Marine Mammal and Biological Oceanography
48 (MB) FY11 Annual Reports. Arlington, Virginia: Office of Naval Research.
49 <http://www.onr.navy.mil/reports/FY11/mbfinne1.pdf>
50

51 Finneran, J.J. and A.K. Jenkins. 2012. Criteria and thresholds for U.S. Navy acoustic and
52 explosive effects analysis. San Diego, California: SPAWAR Systems Center Pacific.
53

54 Finneran, J.J., and C.E. Schlundt. 2009. Auditory weighting functions and frequency-dependent
55 effects of sound in bottlenose dolphins (*Tursiops truncatus*). Pages 130-131 in ONR
56 Marine Mammal Program Review, 7-10 December 2009, Arlington, Virginia.

1
2 Finneran, J.J., and C.E. Schlundt. 2010. Frequency-dependent and longitudinal changes in noise-
3 induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*). Journal of the Acoustical
4 Society of America 128:567-570.
5
6 Finneran, J.J., and C.E. Schlundt. 2011. Subjective loudness level measurements and equal
7 loudness contours in a bottlenose dolphin (*Tursiops truncatus*). Journal of the Acoustical
8 Society of America 130:3124-3136.
9
10 Finneran, J.J., and C.E. Schlundt. 2013. Effects of fatiguing tone frequency on temporary
11 threshold shift in bottlenose dolphins (*Tursiops truncatus*). Journal of the Acoustical Society
12 of America 133:1819-1826.
13
14 Finneran, J.J., C.E. Schlundt, D.A. Carder, J.A. Clark, J.A. Young, J.B. Gaspin, and S.H.
15 Ridgway. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops*
16 *truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling
17 distant signatures of underwater explosions. Journal of the Acoustical Society of America
18 108:417-431.
19
20 Finneran, J.J., C.E. Schlundt, R. Dear, D.A. Carder, and S.H. Ridgway. 2002. Temporary shift in
21 masked hearing thresholds in odontocetes after exposure to single underwater impulses
22 from a seismic watergun. Journal of the Acoustical Society of America 111:2929-2940.
23
24 Finneran, J. J., R. Dear, D.A. Carder, and S.H. Ridgway. 2003. Auditory and behavioral
25 responses of California sea lions (*Zalophus californianus*) to single underwater impulses
26 from an arc-gap transducer. Journal of the Acoustical Society of America 114:1667-1677.
27
28 Finneran, J.J., D.A. Carder, C.E. Schlundt, and S.H. Ridgway. 2005. Temporary threshold shift in
29 bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. Journal of the
30 Acoustical Society of America 118:2696-2705.
31
32 Finneran, J.J., C.E. Schlundt, B. Branstetter, and R.L. Dear. 2007. Assessing temporary
33 threshold shift in a bottlenose dolphin (*Tursiops truncatus*) using multiple simultaneous
34 auditory evoked potentials. Journal of the Acoustical Society of America 122:1249–1264.
35
36 Finneran, J.J., D.A. Carder, C.E. Schlundt, and R.L. Dear. 2010a. Growth and recovery of
37 temporary threshold shift at 3 kHz in bottlenose dolphins: Experimental data and
38 mathematical models. Journal of the Acoustical Society of America 127:3256-3266.
39
40 Finneran, J.J., D.A. Carder, C.E. Schlundt, and R.L. Dear. 2010b. Temporary threshold shift in a
41 bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones. Journal of the
42 Acoustical Society of America 127:3267-3272.
43
44 Fletcher, H., and W.A. Munson. 1933. Loudness, its definition, measurement and calculation.
45 Journal of the Acoustical Society of America 5:82-108.
46
47 Ford, J.K.B., and R.R. Reeves. 2008. Fight or flight: Antipredator strategies of baleen whales.
48 Mammal Review 38:50-86.
49
50 Francis, R.I.C.C., and R. Shotton. 1997. "Risk" in fisheries management: A review. Canadian
51 Journal of Fisheries and Aquatic Science 54:1699–1715.
52
53 Frid, A., and L. Dill. 2002. Human-caused disturbance stimuli as a form of predation risk.
54 Conservation Ecology 6:11: published online.

1 Gedamke, J., N. Gales, and S. Frydman. 2011. Assessing risk of baleen whale hearing loss from
2 seismic surveys: The effect of uncertainty and individual variation. *Journal of the*
3 *Acoustical Society* 129:496-506.
4

5 Hamernik, R.P., W.A. Ahroon, and J.A. Patterson. 1988. Threshold recovery functions following
6 impulse noise trauma. *Journal of the Acoustical Society of America* 84:941-950.
7

8 Hamernik, R.P., W. Qiu, and B. Davis. 2003. The effects of the amplitude distribution of equal
9 energy exposures on noise-induced hearing loss: The kurtosis metric. *Journal of the*
10 *Acoustical Society of America* 114:386-395.
11

12 Harding, G.W., and B.A. Bohne. 2004. Noise-induced hair-cell loss and total exposure energy:
13 Analysis of a large data set. *Journal of the Acoustical Society of America* 115:2207-2220.
14

15 Harwood, J., and K. Stokes. 2003. Coping with uncertainty in ecological advice: lessons from
16 fisheries. *Trends in Ecology and Evolution* 18:617-622.
17

18 Hemilä, S., S. Nummela, A. Berta, and T. Reuter. 2006. High-frequency hearing in phocid and
19 otariid pinnipeds: An interpretation based on inertial and cochlear constraints (L). *Journal*
20 *of the Acoustical Society of America* 120:3463-3466.
21

22 Henderson, D., and R.P. Hamernik. 1982. Asymptotic threshold shift from impulse noise. Pages
23 265-298 in Hamernik, R.P., D. Henderson, and R. Salvi, eds. *New Perspectives on*
24 *Noise-Induced Hearing Loss*. New York: Raven Press.
25

26 Henderson, D., and R.P. Hamernik. 1986. Impulse noise: Critical review. *Journal of the Acoustical*
27 *Society of America* 80:569-584.
28

29 Henderson, D., F. Farzi, and R. Danielson. 1990. The concept of critical level and impulse noise.
30 *Environment International* 16:353-361.
31

32 Henderson, D., V. Spongr, M. Subramaniam, and P. Campo. 1994. Anatomical effects of impact
33 noise. *Hearing Research* 76:101-117.
34

35 Henderson, D., B. Hu, and E. Bielefeld. 2008. Patterns and mechanisms of noise-induced
36 cochlear pathology. Pages 195-217 in Schacht, J., A.N. Popper, and R.R Fay, eds.
37 *Auditory Trauma, Protection, and Repair*. New York: Springer.
38

39 Henderson, D., M. Subramaniam, M.A. Grattona, and S.S. Saunders. 1991. Impact noise: The
40 importance of level, duration, and repetition rate. *Journal of the Acoustical Society of*
41 *America* 89:1350-1357.
42

43 Hirsch, I.J., and R.C. Bilger. 1955. Auditory-Threshold Recovery after Exposures to Pure Tones
44 *Journal of the Acoustical Society of America* 27:1186-1194.
45

46 Houser, D.S., D.A. Helweg, and P.W.B. Moore. 2001. A bandpass filter-bank model of auditory
47 sensitivity in the humpback whale. *Aquatic Mammals* 27:82-91.
48

49 Humes, L.E., L.M. Joellenbeck, and J.S. Durch. 2005. *Noise and Military Service, Implications for*
50 *Hearing Loss and Tinnitus*. Washington, D.C.: National Academies Press.
51

52 Kastak, D., and R.J. Schusterman. 1998. Low-frequency amphibious hearing in pinnipeds:
53 Methods, measurements, noise, and ecology. *Journal of the Acoustical Society of*
54 *America* 103:2216-2228.

1 Kastak, D., R.J. Schusterman, B.L. Southall, and C.J. Reichmuth. 1999. Underwater temporary
2 threshold shift induced by octave-band noise in three species of pinniped. *Journal of the*
3 *Acoustical Society of America* 106:1142-1148.
4

5 Kastak, D., B.L. Southall, R.J. Schusterman, and C. Reichmuth. 2005. Underwater
6 temporary threshold shift in pinnipeds: Effects of noise level and duration. *Journal of the*
7 *Acoustical Society of America* 118:3154-3163.
8

9 Kastak, D., J. Mulsow, A. Ghaul, and C. Reichmuth. 2008. Noise-induced permanent threshold
10 shift in a harbor seal. *Journal of the Acoustical Society of America* 123:2986.
11

12 Kastak, D., C. Reichmuth, M.M. Holt, J. Mulsow, B.L. Southall, and R.J. Schusterman. 2007.
13 Onset, growth, and recovery of in-air temporary threshold shift in a California sea lion
14 (*Zalophus californianus*). *Journal of the Acoustical Society of America*, 122:2916- 2924.
15

16 Kastelein, R.A., W.C. Verboom, and J.M. Terhune. 2009. Underwater detection of tonal signals
17 between 0.125 and 100kHz by harbor seals (*Phoca vitulina*). *Journal of the Acoustical*
18 *Society of America*, 125:1222-1229.
19

20 Kastelein, R.A., R. Gransier, L. Hoek, A. Macleod, and J.M. Terhune. 2012a. Hearing threshold
21 shifts and recovery in harbor seals (*Phocina vitulina*) after octave-band noise exposure at
22 4 kHz. *Journal of the Acoustical Society of America* 132:2745-2761.
23 Kastelein, R.A., R. Gransier, L. Hoek, and J. Olthuis. 2012b. Temporary hearing threshold shifts
24 and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4
25 kHz. *Journal of the Acoustical Society of America* 132:3525-3537.
26

27 Kastelein, R.A., R. Gransier, L. Hoek, and A. Macleod, and J.M. Terhune. 2013a. Auditory and
28 behavioral responses of two harbor seals (*Phoca vitulina*) to playbacks of offshore pile
29 driving sounds, phase1: Behavioral response in one seal, but no TTS.
30

31 Kastelein, R.A., R. Gransier, and L. Hoek. 2013b. Comparative temporary threshold shifts in a
32 harbor porpoise and harbor seal, and severe shift in a seal (L). *Journal of the Acoustical*
33 *Society of America* 134:13-16.
34

35 Kastelein, R.A. R. Gransier, L. Hoek, and M. Rambags. 2013c. Hearing frequency thresholds of
36 harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz
37 tone. *Journal of the Acoustical Society of America* 134:2286-2292.
38

39 Ketten, D.R. 1992. The marine mammal ear: Specializations for aquatic audition and
40 echolocation. Pages 717-750. In: D. W. Webster, R. R. Fay and A. N. Popper, eds. *The*
41 *Evolutionary Biology of Hearing*. Springer-Verlag.
42

43 Ketten, D.R. 1998. Marine mammal auditory systems: A summary of audiometric and anatomical
44 data and its implications for underwater acoustic impacts. NOAA Technical Memorandum
45 NOAA-TM-NMFS-SW FSC-256. La Jolla, California: National Marine Fisheries Service.
46

47 Ketten, D. 2000. Cetacean ears. Pages 43-108 In: W.W.L Au, A.N. Popper, and R.R. Fay, eds.
48 *Hearing by Whales and Dolphins*. New York: Springer.
49

50 Ketten, D.R., and D.C. Mountain. 2009. Beaked and baleen whale hearing: Modeling responses
51 to underwater noise. Washington, D.C.:CNO(N45).
52

53 Kryter, K.D., W.D. Ward, J.D. Miller, and D.H. Eldredge. 1966. Hazardous Exposure to
54 Intermittent and Steady-State Noise. *Journal of the Acoustical Society of America* 39:451-
55 464.
56

1 Kujawa, S.G., and M.C. Liberman. 2009. Adding insult to injury: Cochlear nerve degeneration
2 after “temporary” noise-induced hearing loss. *The Journal of Neuroscience* 29:14077-
3 14085.
4

5 Kyhn, L.A., J. Tougaard, F. Jensen, M. Wahlberg, K. Beedholm, and P.T. Madsen. 2009. Feeding
6 at a high pitch: Source parameters of narrow band high-frequency clicks from
7 echolocating off-shore hourglass dolphins and coastal Hector’s dolphins. *Journal of the*
8 *Acoustical Society of America* 125:1783-1791.
9

10 Kyhn, L.A., F.H. Jensen, K. Beedholm, J. Tougaard, M. Hansen, and P.T. Madsen. 2010.
11 Echolocation in sympatric Peale’s dolphins (*Lagenorhynchus australis*) and
12 Commerson’s dolphins (*Cephalorhynchus commersonii*) producing narrow-band high-
13 frequency clicks. *The Journal of Experimental Biology* 213:1940-1949.
14

15 Laroche, C., R. Héту, and S. Poireir. 1989. The growth of and recovery from TTS in human
16 subjects exposed to impact noise. *Journal of the Acoustical Society of America* 85:1681-
17 1690.
18

19 Lataye, R., and P. Campo. 1996. Applicability of the L_{eq} as a damage-risk criterion: An animal
20 experiment. *Journal of the Acoustical Society of America* 99:1621-1632.
21

22 Levine, S., P. Hofstetter, X.Y. Zheng, and D. Henderson. 1998. Duration and peak level as co-
23 factors in hearing loss from exposure to impact noise. *Scandinavian Audiology*
24 *Supplementum* 48:27-36.
25

26 Lin, H.W., A.C. Furman, S.G. Kujawa, and M.C. Liberman. 2011. Primary neural degeneration in
27 the guinea pig cochlea after reversible noise-induced threshold shift. *Journal of the*
28 *Association for Research in Otolaryngology* 12:605-616.
29

30 Lucifredi, I., and P.J. Stein. 2007. Gray whale target strength measurements and the analysis of
31 the backscattered response. *Journal of the Acoustical Society of America* 121:1383-
32 1391.
33

34 Lucke, K., U. Siebert, P.A. Lepper, and M-A. Blanchet. 2009. Temporary shift in masked hearing
35 thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun
36 stimuli. *Journal of the Acoustical Society of America* 125:4060-4070.
37

38 Lucke, K. 2009. Personal communication via email with Dr. Amy R. Scholik-Schlomer, Office of
39 Protected Resources, National Marine Fisheries Service. 14 August.
40

41 Ludwig, D., R. Hilborn, and C. Waters. 1993. Uncertainty, resource exploitation, and
42 conservation: Lessons from history. *Science* 260:17-36.
43

44 Luther, D.A., and R.H. Wiley. 2009. Production and perception of communicatory signals in a
45 noisy environment. *Biology Letters* 5:183-187.
46

47 Lutz, G.A., and D.C. Hodge. 1971. Recovery from impulse-noise induced TTS in monkeys and
48 men: A descriptive model. *Journal of the Acoustical Society of America* 49:1770-1777.
49

50 Malme, C.I., P.R. Miles, G.W. Miller, W.J. Richardson, D.G. Roseneau, D.H. Thomson, and C.R.
51 Greene, Jr. 1989. Analysis and ranking of the acoustic disturbance potential of petroleum
52 industry activities and other sources of noise in the environment of marine mammals in
53 Alaska. Report No. 6945. Cambridge, Massachusetts: BBN Systems and Technologies
54 Corporation.
55

1 Maslen, K. R. 1981. Towards a better understanding of temporary threshold shift of hearing.
2 Applied Acoustics 14: 281–318.
3

4 Melnick, W. 1977. Temporary threshold shift following 24-hour noise exposure. The Annals of
5 Otology, Rhinology & Laryngology 86:821-826.
6

7 May-Collado, L., and I. Agnarsson. 2006. Cytochrome *b* and Bayesian inference of whale
8 phylogeny. Molecular Phylogenetics and Evolution 38:344-354.
9

10 Miller, J.D. 1974. Effects of noise on people. Journal of the Acoustical Society of America 56:729
11 764.
12

13 Mills, J.H., R.M. Gilbert, and W.Y. Adkins. 1979. Temporary threshold shifts in humans exposed
14 to octave bands of noise for 16 to 24 hours. Journal of the Acoustical Society of America
15 65:1238-1248.
16

17 Mills, J.H., W.Y. Adkins, and R.M. Gilbert. 1981. Temporary threshold shifts produced by
18 wideband noise. Journal of the Acoustical Society of America 70:390-396.
19

20 Mooney, T.A., P.E. Nachtigall, and S. Vlachos. 2009a. Sonar-induced temporary hearing loss in
21 dolphins. Biology Letters 5:565-567.
22

23 Mooney, T.A., P.E. Nachtigall, M. Breese, S. Vlachos, and W.W.L. Au. 2009b. Predicting
24 temporary threshold shifts in a bottlenose dolphin (*Tursiops truncatus*): The effects of
25 noise level and duration. Journal of the Acoustical Society of America 125:1816-1826.
26

27 Mulsow, J., C. Reichmuth, F. Gulland, D.A.S. Rosen, and J.J. Finneran. 2011. Aerial audiograms
28 of several California sea lions (*Zalophus californianus*) and Steller sea lions (*Eumetopias*
29 *jubatus*) measured using single and multiple simultaneous auditory steady-state
30 response methods. The Journal of Experimental Biology 214:1138-1147.
31

32 Nachtigall, P.E., J.L. Pawloski, and W.W. L. Au. 2003. Temporary threshold shifts and recovery
33 following noise exposure in the Atlantic bottlenose dolphin (*Tursiops truncatus*). Journal
34 of the Acoustical Society of America 113:3425-3429.
35

36 Nachtigall, P.E., A. Ya. Supin, J.L. Pawloski, and W.W.L. Au. 2004. Temporary threshold shifts
37 after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using
38 auditory evoked potentials. Marine Mammal Science 20:673-687.
39

40 NIOSH (National Institute for Occupational Safety and Health). 1998. Criteria for a recommended
41 standard: Occupational noise exposure. Cincinnati, Ohio: United States Department of
42 Health and Human Services.
43

44 NOAA (National Oceanic and Atmospheric Administration). 2013. Magnuson-Stevens Act
45 Provisions, National Standard 2-Scientific Information. Federal Register 78(139):43066-
46 43090.
47

48 NRC (National Research Council). 2004. Improving the Use of the “Best Scientific Information
49 Available” Standard in Fisheries Management. Washington, D.C.: National Academy
50 Press.
51

52 Nowacek, D.P., L.H. Thorne, D.W. Johnston, and P.L. Tyack. 2007. Responses of cetaceans to
53 anthropogenic noise. Mammal Review 37:81-115.
54

55 OMB (Office of Management and Budget). 2005. Final information quality bulletin for peer review.
56 Federal Register 70(10):2664-2677.

1 Patenaude, N.J., W.J. Richardson, M.A. Smultea, W.R. Koski, G.W. Miller, B. Würsig, and C.R.
2 Greene, Jr. 2002. Aircraft sound and disturbance to bowhead and beluga whales during
3 spring migration in the Alaskan Beaufort Sea. *Marine Mammal Science* 18:309-335.
4

5 Perrin, W.F., B. Würsig, and J.G.M. Thewissen (Eds). 2008. *Encyclopedia of Marine Mammals*
6 (Second Edition). San Diego, California: Elsevier.
7

8 Parks, S., D.R. Ketten, J.T. O'Malley, and J. Arruda. 2007. Anatomical Predictions of Hearing in
9 the North Atlantic Right Whale. *The Anatomical Record* 290:734-744.
10

11 Patuzzi, R. 1998. Exponential onset and recovery of temporary threshold shift after loud sound:
12 Evidence for long-term inactivation of mechano-electrical transduction channels. *Hearing*
13 *Research* 125:17-38.
14

15 Popov, V.V., A.Y. Supin, D. Wang, K. Wang, L. Dong, and S. Wang. 2011a. Noise-induced
16 temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena*
17 *phocaenoides asiaeorientalis*. *Journal of the Acoustical Society of America* 130:574-584.
18

19 Popov, V.V., V.O. Klishin, D.I. Nechaev, M.G. Pletenko, V.V. Rozhnov, A.Y. Supin, E.V.
20 Sysueva, and M.B. Tarakanov. 2011b. Influence of acoustic noises on the white whale
21 hearing thresholds. *Doklady Biological Sciences* 440:332-334.
22

23 Popov, V.V., A. Ya Supin, V. V Rozhnov, D.I. Nechaev, E.V. Sysuyeva, V.O. Klishin, M.G.
24 Pletenko, and M.B. Tarakanov. 2013. Hearing threshold shifts and recovery after noise
25 exposure in beluga whales, *Delphinapterus leucas*. *The Journal of Experimental Biology*
26 216:1587-1596.
27

28 Price, G.R. 1981. Implications of a critical level in the ear for assessments of noise hazard at high
29 intensities. *Journal of the Acoustical Society of America* 69:171-177.
30

31 Price, G.R., and S. Wansack. 1989. Hazard from intense midrange impulses. *Journal of the*
32 *Acoustical Society of America* 86:2185-2191.
33

34 Punt, A.E., and G.P. Donovan. 2007. Developing management procedures that are robust to
35 uncertainty: lessons from the International Whaling Commission. *International Council for*
36 *the Exploration of the Sea Journal of Marine Science* 64:603-612.
37

38 Quaranta, A., P. Portalatini, and D. Henderson. 1998. Temporary and permanent threshold shift:
39 An overview. *Scandinavian Audiology* 27:75-86.
40

41 Reichmuth, C. 2007. Assessing the hearing capabilities of mysticete whales. A proposed
42 research strategy for the Joint Industry Programme on Sound and Marine Life on 12
43 September.
44 [http://www.soundandmarinelife.org/Site/Products/MysticeteHearingWhitePaper-](http://www.soundandmarinelife.org/Site/Products/MysticeteHearingWhitePaper-Reichmuth.pdf)
45 [Reichmuth.pdf](http://www.soundandmarinelife.org/Site/Products/MysticeteHearingWhitePaper-Reichmuth.pdf).
46

47 Reichmuth, C. 2008. Research Memorandum in Reference to NMFS Marine Mammal Permit
48 1072-1771-00. 17 September.
49

50 Reichmuth, C., M.M. Holt, J. Mulsow, J.M. Sills, and B.L. Southall. 2013. Comparative
51 assessment of amphibious hearing in pinnipeds. *Journal of Comparative Physiology A*
52 199:491-507.
53

54 Richardson, W.J., and C.I. Malme. 1993. Man-made noise and behavioral responses. Pages 631-
55 700. In Burns, J.J., J.J. Montague, and C.J. Cowles, eds. *The Bowhead Whale*. The
56 Society for Marine Mammalogy, Special Publication Number 2.

1
2 Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. Marine mammals and
3 noise. New York: Academic Press.
4

5 Ridgway, S. and Carder. 2001. Assessing hearing and sound production in cetacean species not
6 available for behavioral audiograms: experiences with sperm, pygmy sperm, and gray
7 whales. *Aquatic Mammals* 27:267-276.
8

9 Roberto, M., R.P. Hamernik, R.J. Salvi, D. Henderson, and R. Milone. 1985. Impact noise and the
10 equal energy hypothesis. *Journal of the Acoustical Society of America* 77:1514-1520.
11

12 Saunders, J.C., S.P. Dear, and M.E. Schneider. 1985. The anatomical consequences of acoustic
13 injury: A review and tutorial. *Journal of the Acoustical Society of America* 78:833-860.
14

15 Schlundt, C.E., J.J. Finneran, D.A. Carder, and S.H. Ridgway. 2000. Temporary shift in masked
16 hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales,
17 *Delphinapterus leucas*, after exposure to intense tones. *Journal of the Acoustical Society*
18 *of America* 107:3496-3508.
19

20 Schlundt, C.E., R.L. Dear, D.A. Carder, and J.J. Finneran. 2006. Growth and recovery of
21 temporary threshold shifts in a dolphin exposed to midfrequency tones with durations up
22 to 128 s. *Journal of the Acoustical Society of America* 120:3227.
23

24 SEAMARCO. 2011. Temporary hearing threshold shifts and recovery in a harbor porpoise and
25 two harbor seals after exposure to continuous noise and playbacks of pile driving sounds.
26 SEAMARCO Ref: 2011/01. Harderwijk, The Netherlands: SEAMARCO (Sea Mammal
27 Research Company).
28

29 Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak,
30 D.R. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas, and P.L. Tyack.
31 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic*
32 *Mammals* 33:411-521.
33

34 Spieth, W., and W. Trittipoe. 1958. Intensity and duration of noise exposure and temporary
35 threshold shifts. *Journal of the Acoustical Society of America* 30:710-713.
36

37 Starck, J., E. Toppila, and I. Pyykkö. 2003. Impulse noise and risk criteria. *Noise & Health* 5:63-
38 73.
39

40 Suzuki, Y., and H. Takeshima. 2004. Equal-loudness-level contours for pure tones. *Journal of the*
41 *Acoustical Society of America* 116:918-933.
42

43 Terhune, J.M., and K. Ronald. 1975. Underwater hearing sensitivity of two ringed seals (*Pusa*
44 *hispida*). *Canadian Journal of Zoology* 53:227-231.
45

46 Tougaard, J., and L.A. Kyhn. 2010. Echolocation sounds of hourglass dolphins (*Lagenorhynchus*
47 *cruciger*) are similar to narrow band high-frequency echolocation sounds of the dolphin
48 genus *Cephalorhynchus*. *Marine Mammal Science* 26:239-245.
49

50 Tubelli, A., A. Zosuls, D. Ketten, M. Yamato, and D.C. Mountain. 2012. A prediction of the minke
51 whale (*Balaenoptera acutorostrata*) middle-ear transfer function. *Journal of the Acoustical*
52 *Society of America* 132: 3263-3272.
53

54 Wade, P.R., R.R. Reeves, and S.L. Mesnick. 2012. Social and behavioural factors in cetacean
55 responses to overexploitation: Are odontocetes less “resilient” than mysticetes? *Journal*
56 *of Marine Biology* Article ID 567276,15 pages.

1
2 Ward, W.D. 1960. Recovery from high values of temporary threshold shift. *Journal of the*
3 *Acoustical Society of America* 32:497-500.
4
5 Ward, W.D. 1962. Damage-risk criteria for line spectra. *Journal of the Acoustical Society of*
6 *America* 34:1610-1619.
7
8 Ward, W.D. 1991. The role of intermittence in PTS. *Journal of the Acoustical Society of America*
9 90:164-169.
10
11 Ward, W.D. 1997. Effects of high-intensity sound. Pages 1497-1507 In M.J. Crocker (ed.)
12 *Encyclopedia of Acoustics, Volume III*. New York: John Wiley & Sons.
13
14 Ward, W.D., A. Glorig, and D.L. Sklar. 1958. Dependence of temporary threshold shift at 4 kc on
15 intensity and time. *Journal of the Acoustical Society of America* 30:944-954.
16
17 Ward, W.D., A. Glorig, and D.L. Sklar. 1959. Temporary threshold shift from octave-band noise:
18 Application to damage-risk criteria. *Journal of the Acoustical Society of America* 31:522-
19 528.
20
21 Wartzok, D., and D.R. Ketten. 1999. Marine mammal sensory systems. Pages 117-175 in J.E.
22 Reynolds III and S.A. Rommel, eds. *Biology of Marine Mammals*. Washington, D.C.:
23 Smithsonian Institution Press.
24
25 Watkins, W.A. 1986. Whale reactions to human activities in Cape Cod waters. *Marine Mammal*
26 *Science* 2:251-262.
27
28 Wirsing, A.J., M.R. Heithaus, A. Frid, and L.M. Dill. 2008. Seascapes of fear: Evaluating
29 sublethal predator effects experienced and generated by marine mammals. *Marine*
30 *Mammal Science* 24:1-15.
31
32 Yost, W.A. 2007. *Fundamentals of Hearing: An Introduction*. New York: Academic Press.