TECHNICAL REPORT

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Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)

SSC Pacific

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ACRONYMS AND ABBREVIATIONS

ASW	anti-submarine warfare
AUTEC	Atlantic Underwater Test and Evaluation Center
BRF	behavioral response function
CDF	cumulative truncated normal distribution function
CES	controlled exposure study
dB	decibel
dB re 1 μPa	decibels referenced to 1 microPascal
dB re 1 $\mu Pa^2 \cdot s$	decibels referenced to 1 microPascal—squared—seconds
EIS	environmental impact statement
GAM	Generalized Additive Model
GLM	Generalized Linear Model
GI	gastrointestinal
HF	high-frequency
Hz	hertz
kHz	kilohertz
LF	low-frequency
MF	mid-frequency
NAEMO	Navy Acoustic Effects Model
PRN	pseudorandom noise
psi	pounds per square inch
PTS	permanent threshold shift
SEL	sound exposure level
SLI	slight lung injury

SOCAL	Southern California
SPL	sound pressure level
TM	tympanic membrane
TTS	temporary threshold shift

1 INTRODUCTION

The Navy is required to assess the potential impacts on marine mammals and sea turtles from training and testing activities to maintain compliance with a suite of Federal environmental laws and regulations. These regulations include, but are not limited to, the Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA). In cases where these activities introduce sound or explosive energy into the marine environment, an acoustic effects analysis must be conducted.

The effects analysis begins with mathematical modeling to predict the sound transmission patterns from Navy sources. Navy activities that involve sonar and other transducers, air guns, pile driving, and explosives are modeled. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate specific effects that animals exposed to Navy-generated sound may experience.

This technical report supersedes the 2012 Phase II report Criteria and Thresholds for U.S. Navy Acoustic and Explosives Effects Analysis, and is comprised of three distinct sections that describe the derivation of criteria and thresholds used to predict specific effects to animals exposed to Navy-generated sounds. Specifically, these effects include potential auditory effects (see Section 2, Auditory Weighting Functions and TTS/PTS Exposure Functions), behavioral responses to underwater anthropogenic sounds (see Section 3, Navy Phase III Behavioral Response Criteria for Marine Species), and non-auditory physiological impacts (see Section 4, Navy Phase III Explosive Non-Auditory Injury Criteria).

Appendix A describes the methods for estimating a low-frequency cetacean audiogram. A description of data used to develop the Phase III Navy behavioral response functions can be found in Appendix B. A summary of these criteria for determining acoustic and explosive effects to marine mammals and sea turtles from Navy sound sources is located in Appendix C.

Research on the impacts of anthropogenic sound on marine species has increased dramatically in the past decade. Since the methodology for deriving composite audiograms and associated marine mammal auditory weighting functions, as well as TTS thresholds is data driven, any new information that becomes available has the potential to cause some amount of change for a specific hearing group, but also other hearing groups, if they rely on surrogate data. As such, the reported criteria and thresholds for marine mammals and sea turtles are anticipated to change over time; however, it is not feasible to make changes with the publication of each new data point. Instead, SSC Pacific will periodically examine the best available science and consider the impacts of those studies on its report (with an anticipated revision cycle of three to five years); however, there may be special circumstances that merit evaluation of data on a more accelerated timeline (e.g., the measurement of mysticete hearing thresholds).

2 AUDITORY WEIGHTING FUNCTIONS AND TTS/PTS EXPOSURE FUNCTIONS

2.1 Introduction

This chapter describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects on marine mammals and sea turtles exposed to sonar and other transducers, explosives, pile driving, and air guns. The weighted threshold values and auditory weighting function shapes are summarized in Appendix C.

2.1.1 Impulsive vs. non-impulsive noise

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

2.1.2 Noise-induced threshold shifts

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

2.1.3 Auditory weighting functions

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

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

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

2.1.4 Phase III weighting functions and TTS/PTS thresholds

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

Since the derivation of Phase II acoustic criteria and thresholds, new data have been obtained regarding marine mammal and sea turtle hearing (Dow Piniak et al., 2012; Ghoul & Reichmuth, 2014; Martin et al., 2012; Sills et al., 2014, 2015), marine mammal equal latency contours (Mulsow et al., 2015; Reichmuth et al., 2013; Wensveen et al., 2014), and the effects of noise on marine mammal hearing (Finneran & Schlundt, 2013; Finneran et al., 2015; Kastelein et al., 2012a; Kastelein et al., 2012b; Kastelein et al., 2013a; Kastelein et al., 2013b; Kastelein et al., 2014b; Kastelein et al., 2014c; Kastelein et al., 2015a; Kastelein et al., 2015b; Popov et al., 2013; Popov et al., 2014; Popov et al., 2015b). As a result, new weighting functions and TTS/PTS thresholds have been developed for Phase III. The new criteria and thresholds are based on all relevant data and feature a consistent approach for all species of interest.

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

2.2 Weighting functions and exposure functions

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

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

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

C *weighting function gain* (dB). The value of *C* defines the vertical position of the curve. Changing the value of *C* shifts the function up/down. The value of *C* is often chosen to set the maximum amplitude of *W* to 0 dB (i.e., the value of *C* does not necessarily equal the peak amplitude of the curve).

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

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

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

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

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

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

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

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

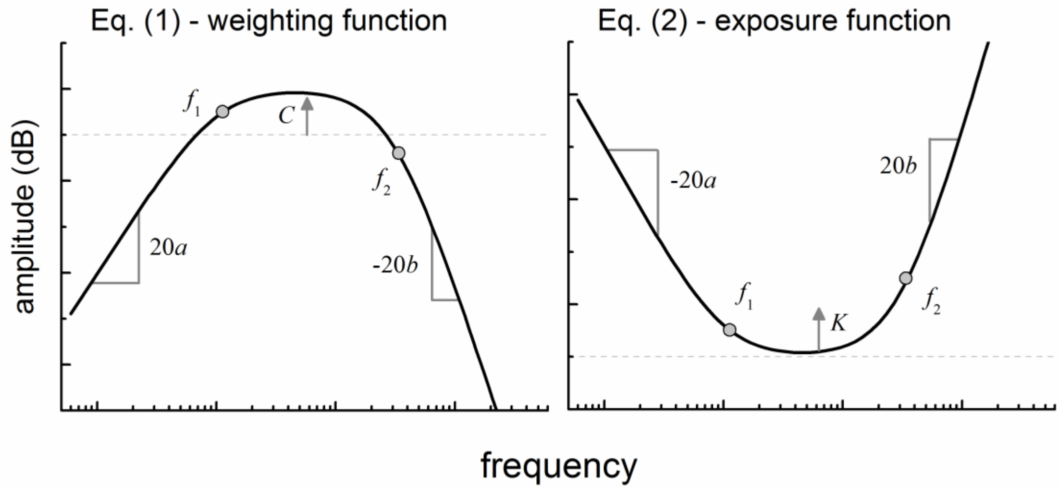

Figure 2-1. Examples of weighting function amplitude (left) described by Eq. (1) and exposure function (right) described by Eq. (2) above. The parameters f_1 and f_2 specify the extent of the filter pass-band, while the exponents a and b control the rate of amplitude change below f_1 and above f_2, respectively.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

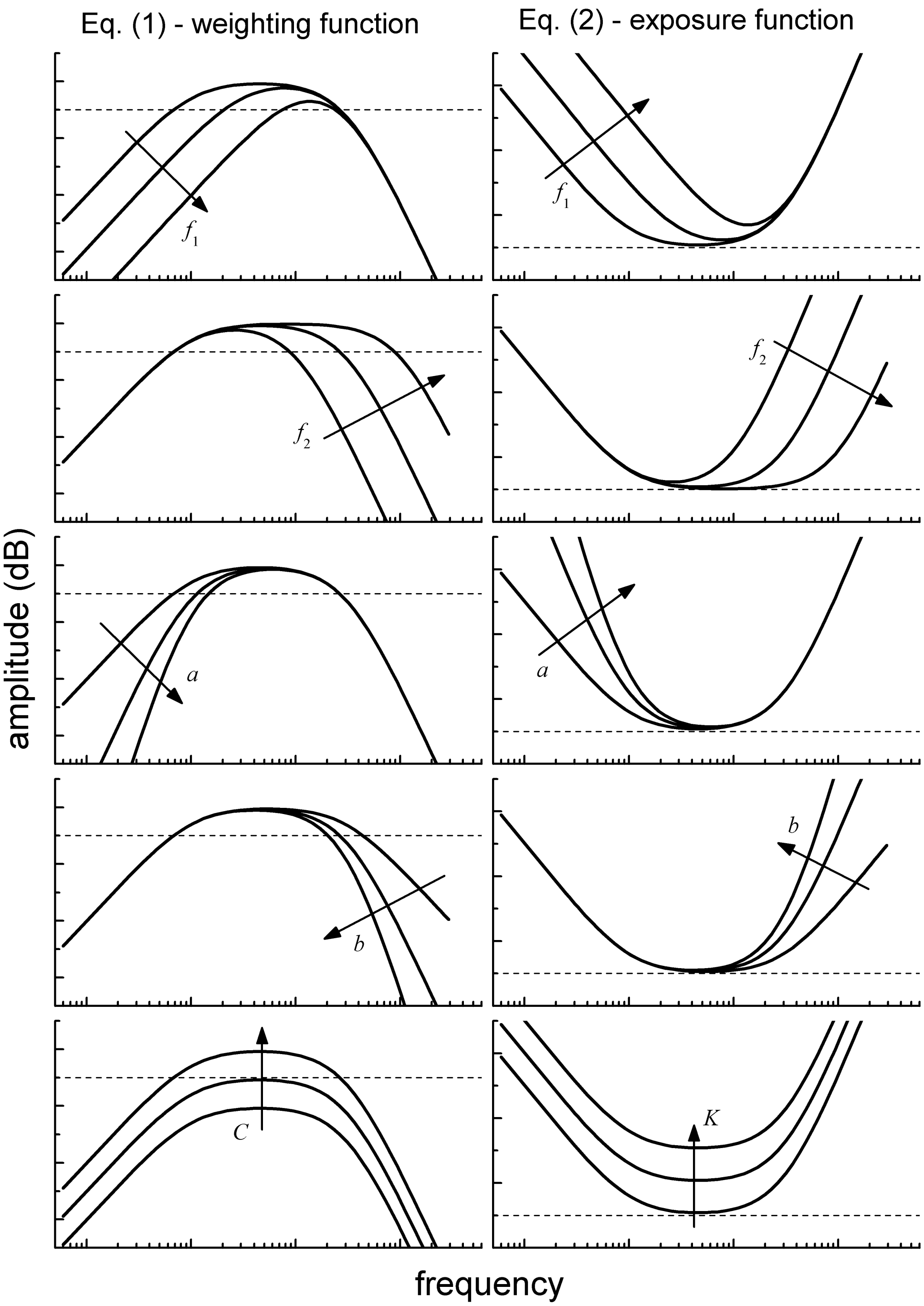

Figure 2-2. Influence of parameter values on the resulting shapes of the weighting functions (left) and exposure functions (right). The arrows indicate the direction of change when the designated parameter is increased.

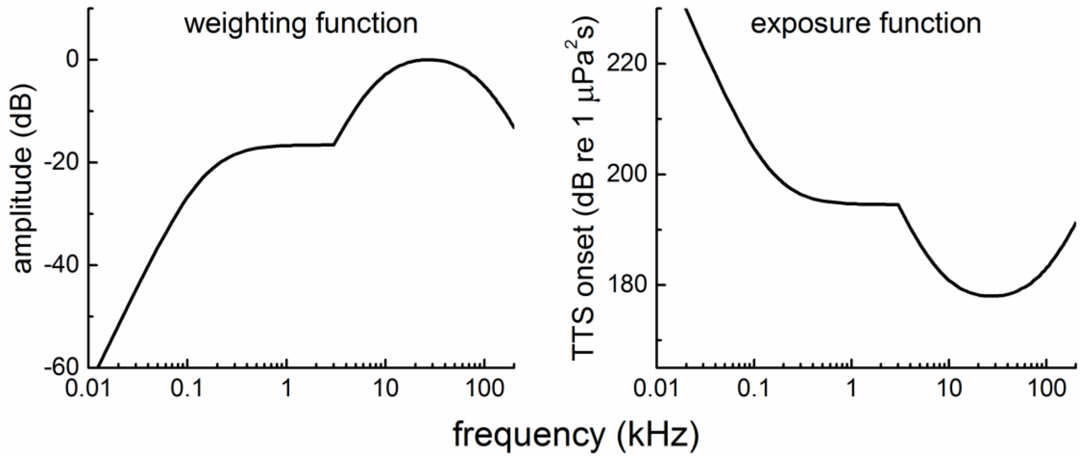

Figure 2-3. (left panel) Navy Phase II weighting function for the mid-frequency cetacean group. This function was used in conjunction with a weighted TTS threshold of 178 dB re 1 μPa^{2}s. For narrowband signals, the effective, weighted TTS threshold at a particular frequency is calculated by adding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

The relationships between Eqs. (1) and (2) may be highlighted by defining the function *X*(*f*) as

$$X(f) = 10\log_{10}\left\{\frac{\left(f/f_1\right)^{2a}}{\left[1+\left(f/f_1\right)^2\right]^a\left[1+\left(f/f_2\right)^2\right]^b}\right\}. \tag{3}$$

The peak value of *X*(*f*) depends on the specific values of f_1, f_2, *a*, and *b* and will not necessarily equal zero. Substituting Eq. (3) into Eqs. (1) and (2) results in

$$W(f) = C + X(f) \tag{4}$$

and

$$E(f) = K - X(f), \tag{5}$$

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

$$W(f_p) = 0 = C + X(f_p). \tag{6}$$

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

$$E(f_p) = T_{wgt} = K - X(f_p). \tag{7}$$

Adding Eqs. (6) and (7) results in

$$T_{wgt} = C + K. \tag{8}$$

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

2.3 Methodology to Derive Function Parameters

Weighting and exposure functions are defined by selecting appropriate values for the parameters C, K, f_1, f_2, a, and b in Eqs. (1) and (2). Ideally, these parameters would be based on experimental data describing the manner in which the onset of TTS or PTS varied as a function of exposure frequency. In other words, a weighting function for TTS should ideally be based on TTS data obtained using a range of exposure frequencies, species, and individual subjects within each species group. However, at present, there are only limited data for the frequency-dependency of TTS in marine mammals and no TTS or PTS data for sea turtles. Therefore, weighting and exposure function derivations relied upon auditory threshold measurements (audiograms), equal latency contours, anatomical data, and TTS data when available.

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

Weighting and exposure function derivation consisted of the following steps:

1. Marine species were divided into nine groups based on auditory, ecological, and phylogenetic relationships among species and the medium (air or water) in which they could be exposed.

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

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

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

5. For species groups for which TTS onset data exist, K was adjusted to minimize the squared error between Eq. (2) and the steady-state (non-impulsive) TTS

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

6. The constant *C* was defined to set the peak amplitude of the function defined by Eq. (1) to zero. This is mathematically equivalent to setting C equal to the difference between the weighted threshold and *K* [see Eq. (8)].

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

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

The remainder of this document addresses these steps in detail.

2.4 Marine Animal Species Groups

Marine mammal and sea turtles were divided into nine groups (Table 2-1), with the same weighting function and TTS/PTS thresholds used for all species within a group. Species were grouped by considering their known or suspected audible frequency range, auditory sensitivity, ear anatomy, and acoustic ecology (i.e., how they use sound), as has been done previously (Finneran & Jenkins, 2012a; Ketten, 2000; Southall et al., 2007).

2.4.1 Low-frequency (LF) cetaceans

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

2.4.2 Mid-frequency (MF) cetaceans

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

2.4.3 High-frequency (HF) cetaceans

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

2.4.4 Sirenians

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

2.4.5 Phocids

This group contains all earless seals or “true seals,” including all Arctic and Antarctic ice seals, harbor or common seals, gray seals and inland seals, elephant seals, and monk seals. Since these animals are amphibious, weighting functions and TTS/PTS thresholds are included for both airborne and underwater exposure. Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group.

2.4.6 Otariids and other non-phocid marine carnivores

This group contains all eared seals (fur seals and sea lions), walruses, sea otters, and polar bears. The division of marine carnivores by placing phocids in one group and all others into a second group was made after considering auditory anatomy and measured audiograms for the various species and noting the similarities between the non-phocid audiograms (Figure 2-4). Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group. Separate weighting functions and TTS/PTS thresholds are included for airborne and underwater exposure.

2.4.7 Sea turtles

This group contains all sea turtles (families Cheloniidae and Dermochelyidae). Most audiometric information has been obtained via AEP measurements, though some behavioral data exist. Sea turtle functional hearing is restricted to relatively low frequencies, below approximately 2 kHz, and they have relatively poor auditory sensitivity.

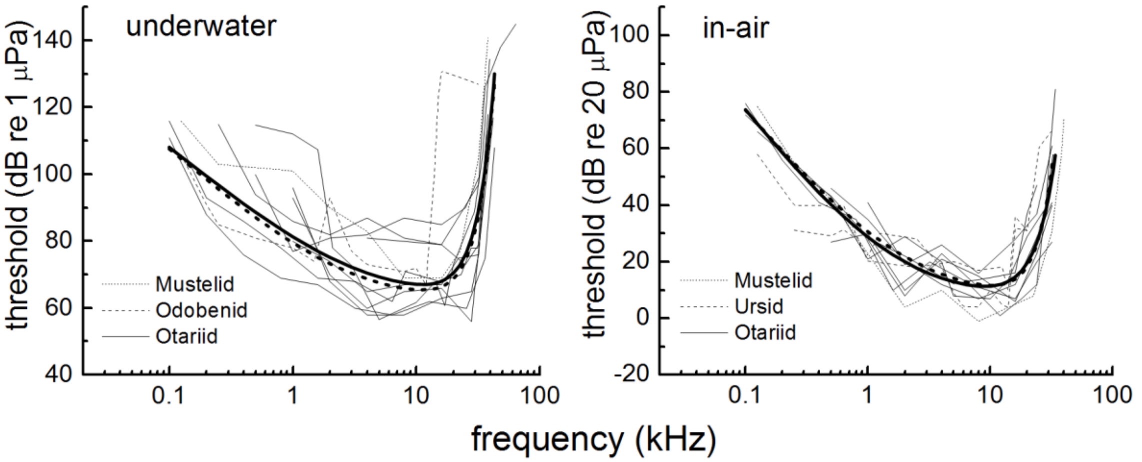

Figure 2-4. Comparison of Otariid, Mustelid, Odobenid, and Ursid psychophysical hearing thresholds measured underwater (left) and in-air (right). The thick, solid line is the composite audiogram based on data for all species. The thick, dashed line is the composite audiogram based on the otariids only.

Table 2-1. Species group designations for Navy Phase III auditory weighting functions.

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

2.5 Composite Audiograms

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

> 1. For marine mammal species groups with three or more behavioral audiograms (all groups except LF cetaceans), only behavioral (no AEP) data were used. Mammalian AEP thresholds are typically elevated from behavioral thresholds in a frequency-dependent manner, with increasing discrepancy between AEP and behavioral thresholds at the lower frequencies where there is a loss of phase synchrony in the neurological responses and a concomitant increase in measured AEP thresholds. The frequency-dependent relationship between the AEP and behavioral data is problematic for defining the audiogram slope at low frequencies, since the AEP data will systematically over-estimate thresholds and therefore over-estimate the low-frequency slope of the audiogram. As a result of this rule, behavioral data were used for all marine mammal groups. For sea turtles, the relationships between AEP and behavioral threshold data are less clear and there were insufficient data to rely on behavioral thresholds alone, therefore both behavioral and AEP data were used for sea turtles. Note that for all species groups, AEP threshold data were still used for interpreting the hearing ability of various species and determining the group to which they should belong.
>
> For the low-frequency cetaceans, for which no behavioral or AEP threshold data exist, hearing thresholds were estimated by synthesizing information from anatomical measurements, mathematical models of hearing, and animal vocalization frequencies (see Appendix A).
>
> 2. Data from an individual animal were included only once at a particular frequency. If data from the same individual were available from multiple studies, data at overlapping frequencies were averaged.
>
> 3. Individuals with obvious high-frequency hearing loss for their species or aberrant audiograms (e.g., obvious notches or thresholds known to be elevated for that species due to masking or hearing loss) were excluded.
>
> 4. Linear interpolation was performed within the threshold data for each individual to estimate a threshold value at each unique frequency present in any of the data for that species group. This was necessary to calculate descriptive statistics at each frequency without excluding data from any individual subject.
>
> 5. Composite audiograms were determined using both the original threshold values from each individual (in dB re 1 µPa or dB re 20 µPa) and normalized thresholds obtained by subtracting the lowest threshold value for that subject.

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

$$T(f) = T_0 + A\log_{10}\left(1+\frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \tag{9}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are fitting parameters. The median value was used to reduce the influence of outliers. The particular form of Eq. (9) was chosen to provide linear-log rolloff with variable slope at low frequencies and a steep rise at high frequencies. The form is similar to that used by Popov et al. (2007) to describe dolphin audiograms; the primary difference between the two is the inclusion of two frequency parameters in Eq. (9), which allows a more shallow slope in the region of best sensitivity. Equation (9) was fit to the median threshold data using nonlinear regression (National Instruments LabVIEW, 2015). The fit of Eq. (9) to the sea turtle data was unsuccessful, therefore the median values were used rather than the fitted curve. The resulting fitting parameters and goodness of fit values (R^2) are provided in Table 2-3 and Table 2-4 for the original and normalized data, respectively. Equation (9) was also used to describe the shape of the estimated audiogram for the LF cetaceans, with the parameter values chosen to provide reasonable thresholds based on the limited available data regarding mysticete hearing (see Appendix A for details).

Figure 2-5 and Figure 2-6 show the original and normalized threshold data, respectively, as well as the composite audiograms based on the fitted curve (or median values for sea turtles). The composite audiograms for each species group are compared in Figure 2-7 . To allow comparison with other audiograms based on the original threshold data, the lowest threshold for the low-frequency cetaceans was estimated to be 54 dB re 1 µPa, based on the median of the thresholds for the other in-water species groups (MF, HF, SI, OW, PW). From the composite audiograms, the frequency of lowest threshold, f_0, and the slope at the lower frequencies, s_0, were calculated (Table 2-5). For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one octave (sea turtles) or one decade (all others) beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A; Figure 2-7).

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

Group	*Reference*	*Species*	*Subjects*
MF	(Finneran et al., 2005b)	*Delphinapterus leucas*	Beethoven
	(Szymanski et al., 1999)	*Orcinus orca*	Yaka, Vigga
	(Nachtigall et al., 1995)	*Grampus griseus*	N/a
	(Kastelein et al., 2003)	*Stenella coeruleoalba*	Meyen
	(Lemonds, 1999)	*Tursiops truncatus*	Itsi Bitsy
	(Brill et al., 2001)	*Tursiops truncatus*	CAS
	(Ljungblad et al., 1982)	*Tursiops truncatus*	12-y male
	(Johnson, 1967)	*Tursiops truncatus*	Salty
	(Sauerland & Dehnhardt, 1998)	*Sotalia fluviatilis*	Paco
	(Johnson et al., 1989)	*Delphinapterus leucas*	2-y female
	(White et al., 1977)	*Delphinapterus leucas*	Edwina, Kojak
	(Awbrey et al., 1988)	*Delphinapterus leucas*	Kojak, female, male
	(Thomas et al., 1988)	*Pseudorca crassidens*	I'a nui hahai
	(Finneran et al., 2010a)	*Tursiops truncatus*	TYH
	(Schlundt et al., 2008)	*Tursiops truncatus*	WEN
	(Ridgway et al., 2001)	*Delphinapterus leucas*	MUK, NOC
	(Tremel et al., 1998)	*Lagenorhynchus obliquidens*	female
HF	(Jacobs & Hall, 1972)	*Inia geoffrensis*	male
	(Kastelein et al., 2002a)**	*Phocoena phocoena*	PpSH047
	(Kastelein et al., 2010)	*Phocoena phocoena*	Jerry
	(Kastelein et al., 2015d)	*Phocoena phocoena*	ID No. 04
OW	(Moore & Schusterman, 1987)	*Callorhinus ursinus*	Lori, Tobe
	(Babushina et al., 1991)	*Callorhinus ursinus*	N/a
	(Kastelein et al., 2002b)	*Odobenus rosmarus*	Igor
	(Mulsow et al., 2012)	*Zalophus californianus*	JFN
	(Reichmuth & Southall, 2012)	*Zalophus californianus*	Rio, Sam
	(Reichmuth et al., 2013)	*Zalophus californianus*	Ronan
	(Kastelein et al., 2005b)	*Eumetopias jubatus*	EjZH021, EjZH022
	(Ghoul & Reichmuth, 2014)	*Enhydra lutris nereis*	Charlie
PW	(Kastak & Schusterman, 1999)	*Mirounga angustirostris*	Burnyce
	(Terhune, 1988)	*Phoca vitulina*	N/a
	(Reichmuth et al., 2013)	*Phoca vitulina*	Sprouts
	(Kastelein et al., 2009)	*Phoca vitulina*	01, 02
	(Sills et al., 2014)	*Phoca largha*	Amak, Tunu
	(Sills et al., 2015)	*Pusa hispida*	Nayak
SI	(Mann et al., 2009)	*Trichechus manatus*	Buffet, Hugh
	(Gerstein et al., 1999)	*Trichechus manatus*	Stormy, Dundee

Group	***Reference***	***Species***	***Subjects***
TU	(Bartol & Ketten, 2006)	*Chelonia mydas*	1,2,D,C,X,6
	(Bartol & Ketten, 2006)	*Lepidochelys kempii*	1
	(Martin et al., 2012)	*Caretta caretta*	female 31
	(Dow Piniak et al., 2012)	*Chelonia mydas*	R1,L2,R3,L3A,L4,L4A
	(Dow Piniak et al., 2012)	*Dermochelys coriacea*	11,12,13,14,15,16,17,18,19,20,21
	(Dow Piniak et al., 2012)	*Eretmochelys imbricata*	3,4,6,7,10
OA	(Moore & Schusterman, 1987)	*Callorhinus ursinus*	Lori, Tobe, Rocky
	(Babushina et al., 1991)	*Callorhinus ursinus*	N/a
	(Mulsow & Reichmuth, 2010)	*Eumetopias jubatus*	Astro
	(Mulsow et al., 2011)	*Zalophus californianus*	JFN
	(Reichmuth et al., 2013)	*Zalophus californianus*	Rio
	(Owen & Bowles, 2011)	*Ursus maritimus*	N/a
	(Ghoul & Reichmuth, 2014)	*Enhydra lutris nereis*	Charlie
PA	(Reichmuth et al., 2013)	*Phoca vitulina*	Sprouts
	(Sills et al., 2014)	*Phoca largha*	Amak, Tunu
	(Sills et al., 2015)	*Pusa hispida*	Nayak

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

Table 2-3. Composite audiogram parameters values for use in Eq. (9). For all groups except LF cetaceans, values represent the best-fit parameters from fitting Eq. (9) to experimental threshold data. For the low-frequency cetaceans, parameter values for Eq. (9) were estimated as described in Appendix A. Fits to the sea turtle data were unsuccessful.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	*A*	*B*	R^2
LF	53.19	0.412	9.4	20	3.2	–
MF	46.2	25.9	47.8	35.5	3.56	0.977
HF	46.4	7.57	126	42.3	17.1	0.968
SI	-40.4	3990	3.8	37.3	1.7	0.982
OW	63.1	3.06	11.8	30.1	3.23	0.939
PW	43.7	10.2	3.97	20.1	1.41	0.907
TU	–	–	–	–	–	–
OA	6.24	1.54	8.24	55.6	2.76	0.978
PA	-110	5.56	1.02×10^{-6}	69.1	0.289	0.973

Table 2-4. Normalized composite audiogram parameters values for use in Eq. (9). For all groups except LF cetaceans, values represent the best-fit parameters after fitting Eq. (9) to normalized threshold data. For the low-frequency cetaceans, parameter values for Eq. (9) were estimated as described in Appendix A. Fits to the sea turtle data were unsuccessful.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	*A*	*B*	R^2
LF	-0.81	0.412	9.4	20	3.2	–
MF	3.61	12.7	64.4	31.8	4.5	0.960
HF	2.48	9.68	126	40.1	17	0.969
SI	-109	5590	2.62	38.1	1.53	0.963
OW	2.36	0.366	12.8	73.5	3.4	0.958
PW	-39.6	368	2.21	20.5	1.23	0.907
TU	–	–	–	–	–	–
OA	-1.55	1.6	8.66	54.9	2.91	0.968
PA	-71.3	4.8	6.33×10^{-5}	63	0.364	0.975

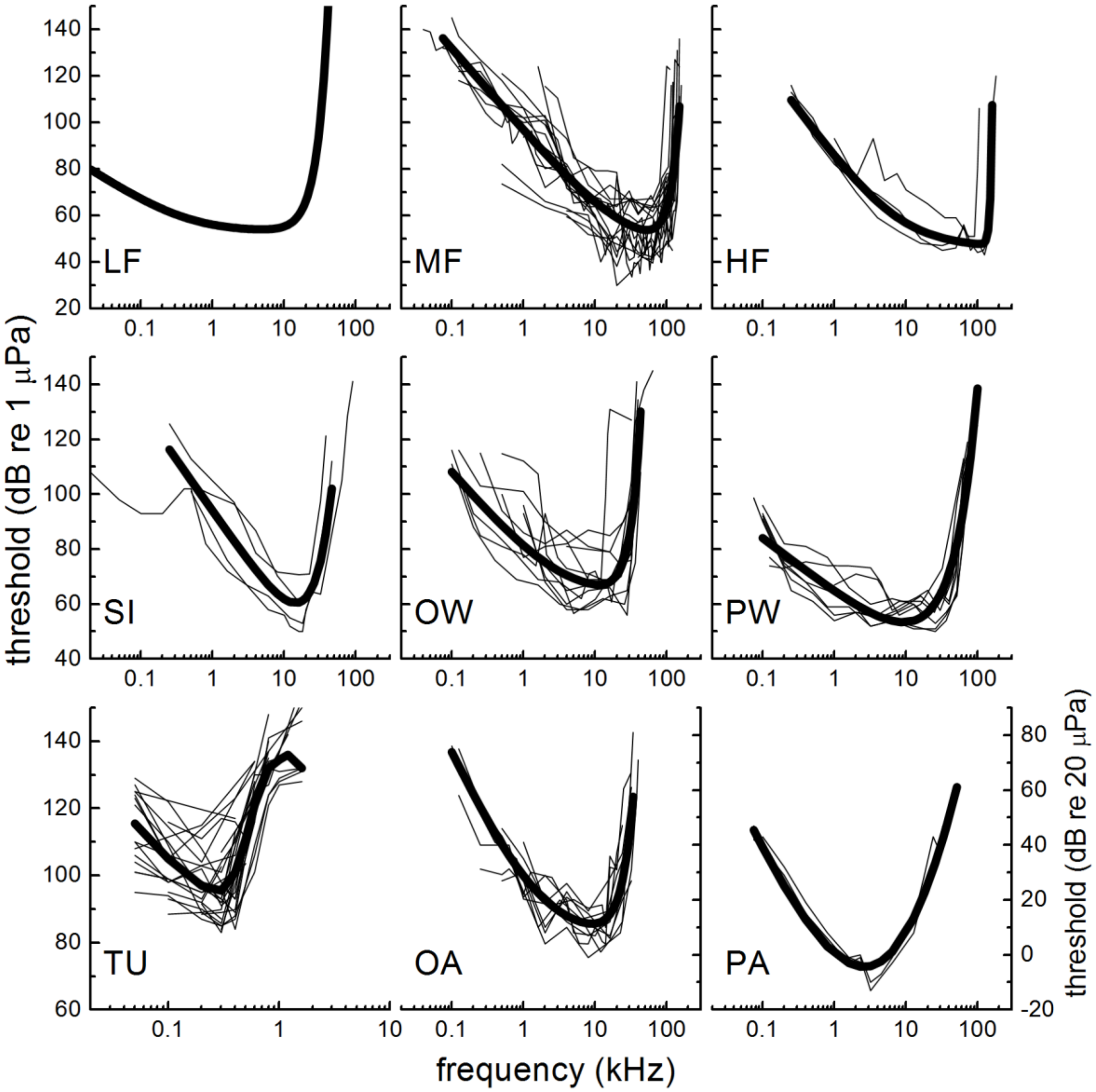

Figure 2-5. Thresholds and composite audiograms for the nine species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the median threshold at each frequency (sea turtles), predicted threshold curve (LF cetaceans), or the best fit of Eq. (9) to experimental data (all other groups). Thresholds are expressed in dB re 1 µPa for underwater data and dB re 20 µPa for in-air data (groups OA and PA only). Derivation of the LF cetacean curve is described in Appendix A. The minimum threshold for the LF cetaceans was estimated to be 54 dB re 1 µPa, based on the median of the lowest thresholds for the marine mammal groups in water (groups MF, HF, SI, OW, PW).

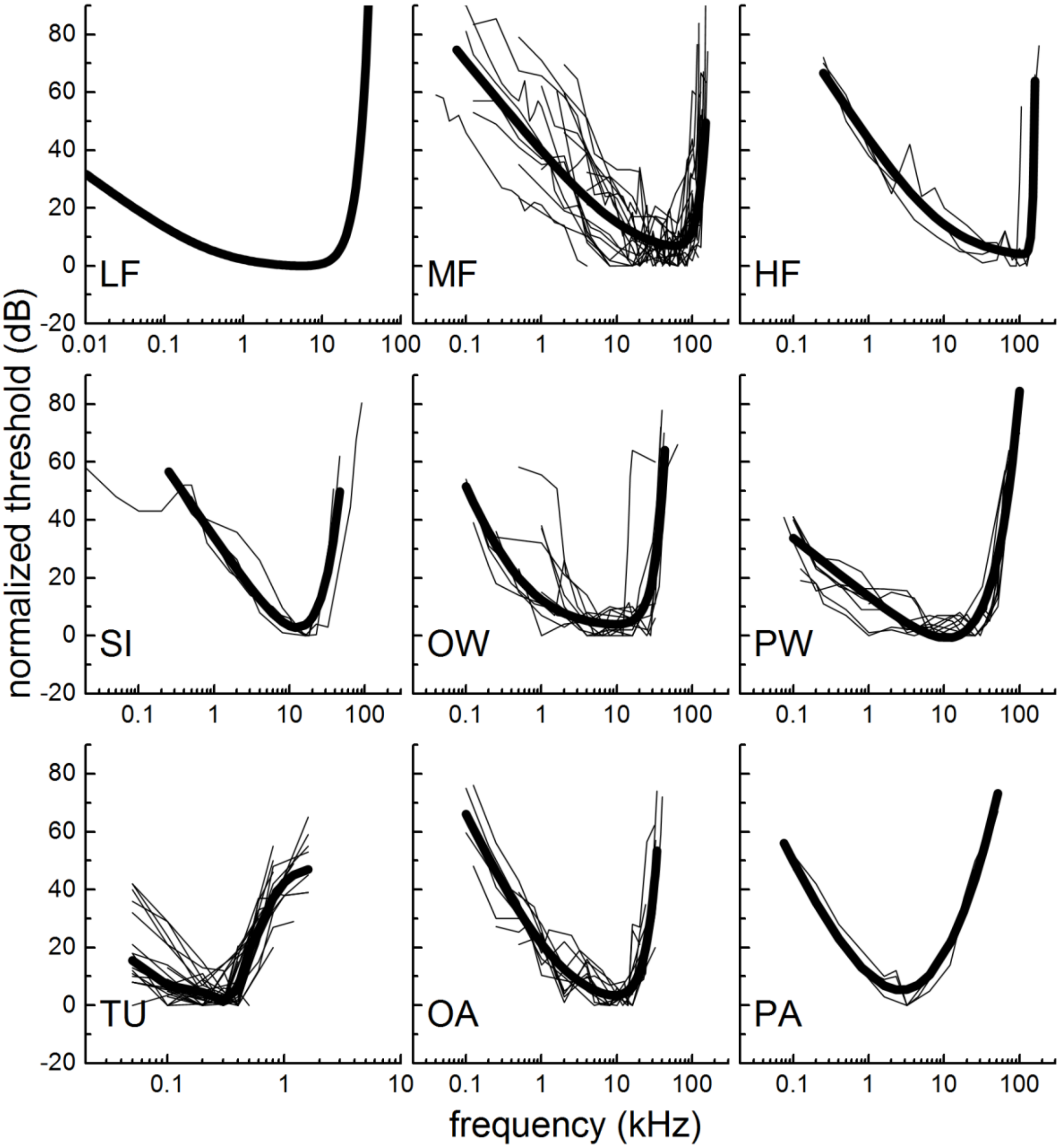

Figure 2-6. Normalized thresholds and composite audiograms for the nine species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the median threshold at each frequency (sea turtles), predicted threshold curve (LF cetaceans), or the best fit of Eq. (9) to experimental data (all other groups). Thresholds were normalized by subtracting the lowest value for each individual data set (i.e., within-subject). Composite audiograms were then derived from the individually normalized thresholds (i.e., the composite audiograms were not normalized and may have a minimum value ≠ 0). Derivation of the LF cetacean curve is described in Appendix A.

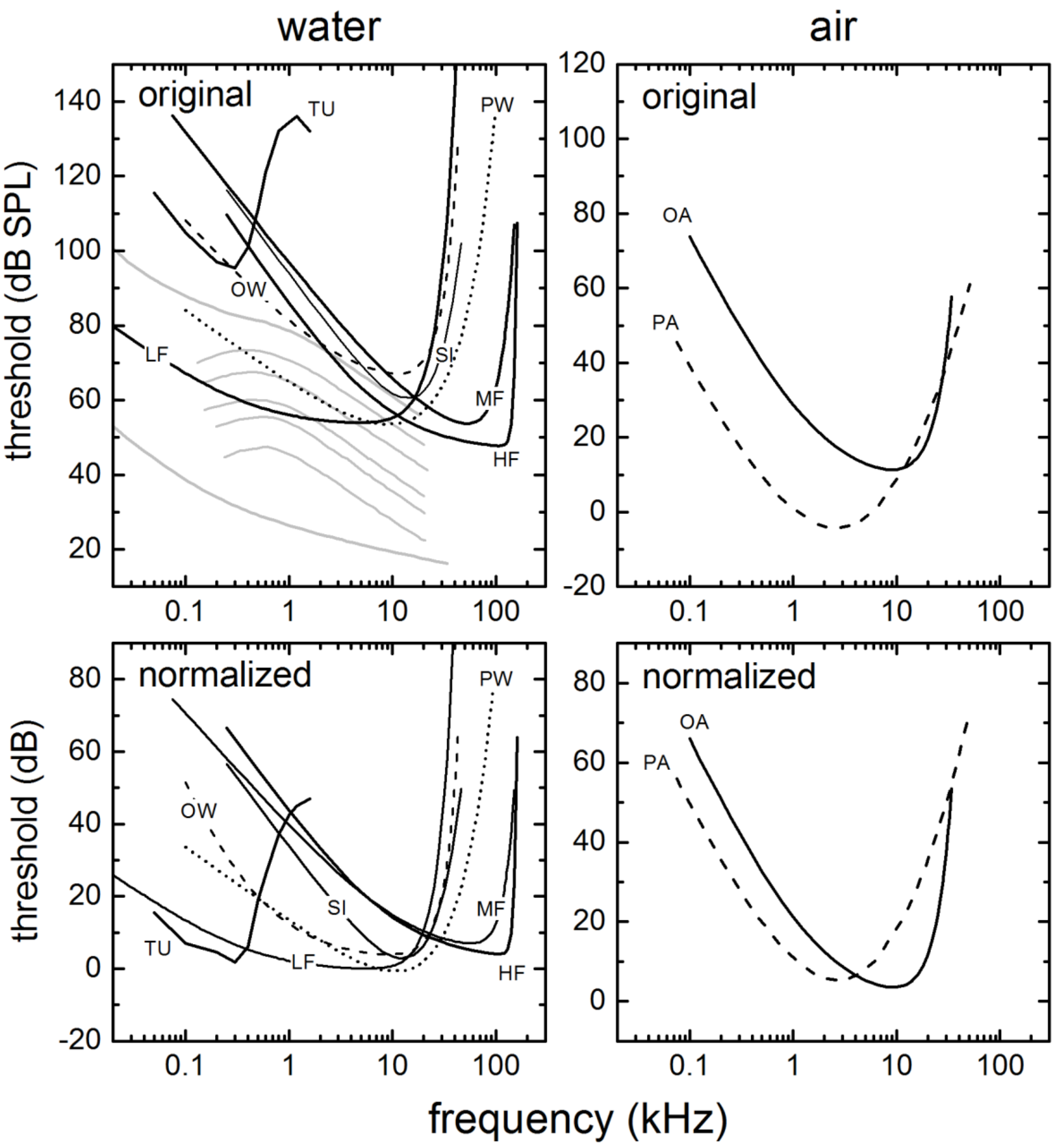

Figure 2-7. Composite audiograms for the various species groups underwater (left) and in-air (right), derived with the original data (upper) and normalized data (lower). Thresholds in upper panels are expressed in dB re 1 μPa for underwater data and dB re 20 μPa for in-air data. The gray lines in the upper left panel represent ambient noise spectral density levels (referenced to the left ordinate, in dB re 1 $\mu Pa^2/Hz$) corresponding to the limits of prevailing noise and various sea-state conditions, from 0.5 to 6 (National Research Council, 2003).

Table 2-5. Frequency of best hearing (f_0) and the magnitude of the low-frequency slope (s_0) derived from composite audiograms and equal latency contours. For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one octave (sea turtles) or one decade (all others) beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A). Equal latency slopes were calculated from the available equal latency contours (Figure 2-8).

Group	*Original data composite audiogram*		*Normalized data composite audiogram*		*Equal latency curves*
	f_0 *(kHz)*	s_0 *(dB/decade)*	f_0 *(kHz)*	s_0 *(dB/decade)*	s_0 *(dB/decade)*
LF	5.6	20	5.6	20	—
MF	55	35	58	31	31
HF	105	37	105	36	50
SI	16	36	12	37	—
OW	12	27	10	39	—
PW	8.6	19	13	20	—
TU	0.30	35	0.30	28	—
OA	10	45	10	45	27
PA	2.3	41	2.3	42	41

2.6 Equal Loudness Data

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

2.7 Equal Latency Data

Reaction times to acoustic tones have been measured in several marine mammal species and used to derive equal latency contours and weighting functions (Mulsow et al., 2015; Reichmuth et al., 2013; Wensveen et al., 2014). Unlike the dolphin equal loudness data, the latency data extend to frequencies below 1 kHz and may be used to estimate the slopes of auditory weighting functions at lower frequencies (Figure 2-8Figure 2-1).

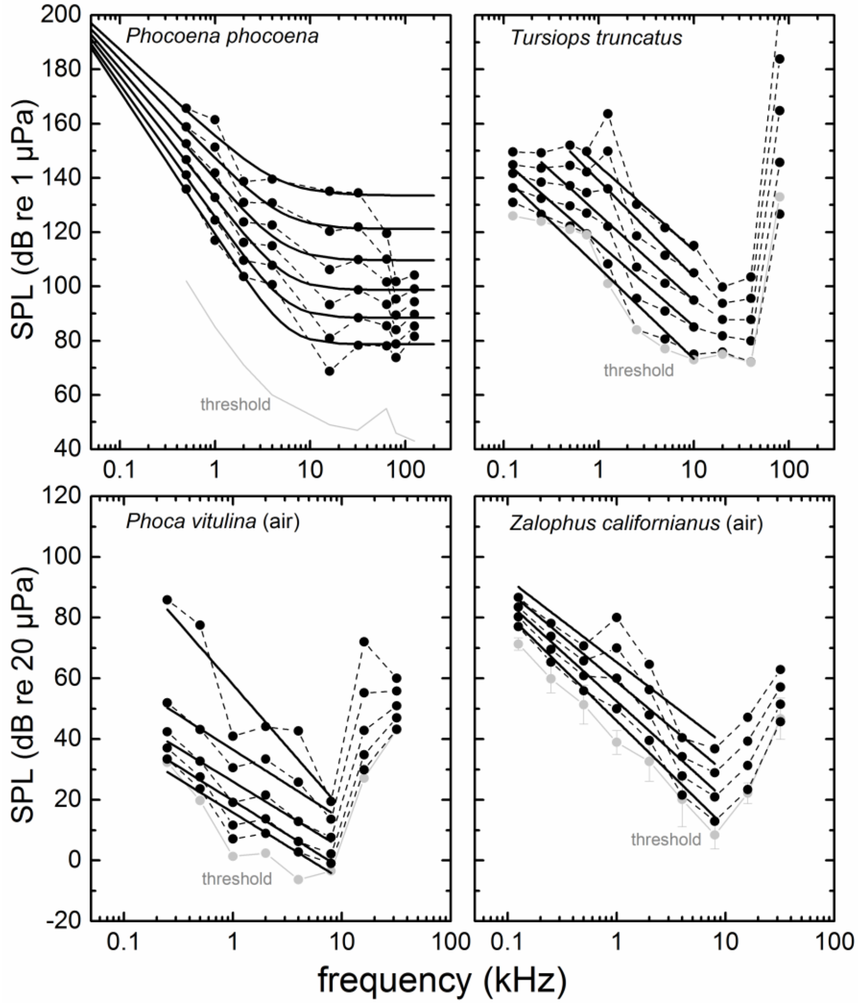

Figure 2-8. Marine mammal equal latency contours are available for *Phocoena phocoena* (Wensveen et al., 2014), *Tursiops truncatus* (Mulsow et al., 2015), *Phoca vitulina* (Reichmuth et al., 2013), and *Zalophus californianus* (Mulsow et al., 2015). The slopes for the contours at low frequencies were obtained from the literature (*Phocoena phocoena*) or calculated from the best linear-log fits to the lower frequency data. The slope of the contour passing through an SPL approximately 40 dB above the threshold at f_0 was selected as the most appropriate based on: (1) human A-weighting, (2) observations that the relationship between equal latency and loudness can break down at higher sensation levels, and (3) for many data sets the slopes increase at higher SPLs rather than decrease as expected. The resulting slopes are listed in Table 2-5.

2.8 TTS Data

2.8.1 Non-impulsive (steady-state) exposures - TTS

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

To estimate TTS onset values, only TTS data from psychophysical (behavioral) hearing tests were used. Studies have shown differences between the amount of TTS from behavioral threshold measurements and that determined using AEP thresholds (Figure 2-9). TTS determined from AEP thresholds is typically larger than that determined behaviorally, and AEP-measured TTS of up to ~ 10 dB has been observed with no corresponding change in behavioral thresholds (Finneran et al., 2007). Although these data suggest that AEP amplitudes and thresholds provide more sensitive indicators (than behavioral thresholds) of the auditory effects of noise, Navy acoustic impact analyses use TTS both as an indicator of the disruption of behavioral patterns that are mediated by the sense of hearing and to predict when the onset of PTS is likely to occur. Navy analyses assume that exposures resulting in a NITS > 40 dB measured a few minutes after exposure will result in some amount of residual PTS. This is based on relationships observed in early human TTS studies utilizing psychophysical threshold measurements. To date, there have been no reports of PTS in a marine mammal whose initial behavioral threshold shift was 40 dB or less; however, behavioral shifts of 35 to 40 dB have required multiple days to recover, suggesting that these exposures are near those capable of resulting in PTS. In contrast, studies utilizing AEP measurements in marine mammals have reported TTSs of 45 dB that recovered in 40 min and 60 dB that recovered in < 24 h, suggesting that these exposures were not near those capable of resulting in PTS (Popov et al., 2013).

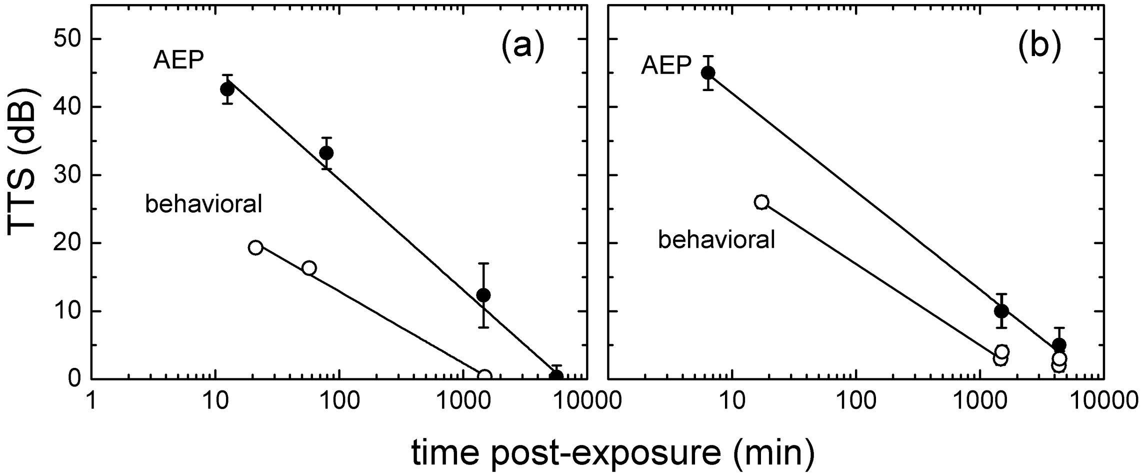

Figure 2-9. TTS measured using behavioral and AEP methods do not necessarily agree, with marine mammal studies reporting larger TTS obtained using AEP methods. For the data above, thresholds were determined using both techniques before and after the same noise exposure. Hearing thresholds were measured at 30 kHz. Behavioral thresholds utilized FM tones with 10% bandwidth. AEP thresholds were based on AM

tones with a modulation frequency of 1.05 kHz. Noise exposures consisted of (a) a single, 20-kHz tone with duration of 64 s and SPL of 185 dB re 1 µPa (SEL = 203 dB re 1 µPa^{2}s) and (b) three 16-s tones at 20 kHz, with mean SPL = 193 dB re 1 µPa (cumulative SEL = 210 dB re 1 µPa^{2}s). Data from Finneran et al. (2007).

To determine TTS onset for each subject, the amount of TTS observed after exposures with different SPLs and durations were combined to create a single TTS growth curve as a function of SEL. The use of (cumulative) SEL is a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles. This is referred to as an "equal energy" approach, since SEL is related to the energy of the sound and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound. It is well-known that the equal energy rule will over-estimate the effects of intermittent noise, since the quiet periods between noise exposures will allow some recovery of hearing compared to noise that is continuously present with the same total SEL (Ward, 1997). For continuous exposures with the same SEL but different durations, the exposure with the longer duration will also tend to produce more TTS (Finneran et al., 2010a; Kastak et al., 2007; Mooney et al., 2009). Despite these limitations, however, the equal energy rule is still a useful concept, since it includes the effects of both noise amplitude and duration when predicting auditory effects. SEL is a simple metric, allows the effects of multiple noise sources to be combined in a meaningful way, has physical significance, and is correlated with most TTS growth data reasonably well — in some cases even across relatively large ranges of exposure duration see (Finneran, 2015). The use of cumulative SEL for Navy sources will always over-estimate the effects of intermittent or interrupted sources, and the majority of Navy sources feature durations shorter than the exposure durations typically utilized in marine mammal TTS studies, therefore the use of (cumulative) SEL will tend to over-estimate the effects of many Navy sound sources.

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

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

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

Figure 2-10 through Figure 2-13 show all behavioral and AEP TTS data to which growth curves defined by Eq. (10) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Table 2-6.

2.8.2 Non-impulsive (steady-state) exposures - PTS

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

A variety of terrestrial and marine mammal data sources (Kryter et al., 1965; Miller et al., 1963; Ward, 1960; Ward et al., 1958, 1959) indicate that threshold shifts up to 40 to 50 dB may be induced without PTS, and that 40 dB is a conservative upper limit for threshold shift to prevent PTS; i.e., for impact analysis, 40 dB of NITS is an upper limit for reversibility and that any additional exposure will result in some PTS. This means that 40 dB of TTS, measured a few minutes after exposure, can be used as a conservative estimate for the onset of PTS. An exposure causing 40 dB of TTS is therefore considered equivalent to PTS onset.

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

2.8.3 Impulsive exposures

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

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

Several impulsive noise exposure studies have also been conducted without measurable (behavioral) TTS. Finneran et al. (2000) exposed dolphins and belugas to single impulses from an "explosion simulator" (maximum unweighted SEL = 179 dB re 1 $\mu Pa^2 s$, peak SPL = 217 dB re 1 µPa) and Finneran et al. (2015) exposed three dolphins to sequences of 10 impulses from a seismic airgun (maximum unweighted cumulative SEL = 193 to 195 dB re 1 $\mu Pa^2 s$, peak SPL =196 to 210 dB re 1 µPa) without measurable TTS. Finneran et al. (2003b) exposed two sea lions to single impulses from an arc-gap transducer with no measurable TTS (maximum unweighted SEL = 163 dB re 1 $\mu Pa^2 s$, peak SPL = 203 dB re 1 µPa). Reichmuth et al. (2016) exposed two spotted seals (*Phoca largha*) and two ringed seals (*Pusa hispida*) to single impulses from a 10 in^3 sleeve airgun with no measurable TTS (maximum unweighted SEL = 181 dB re 1 $\mu Pa^2 s$, peak SPL ~ 203 dB re 1 µPa).

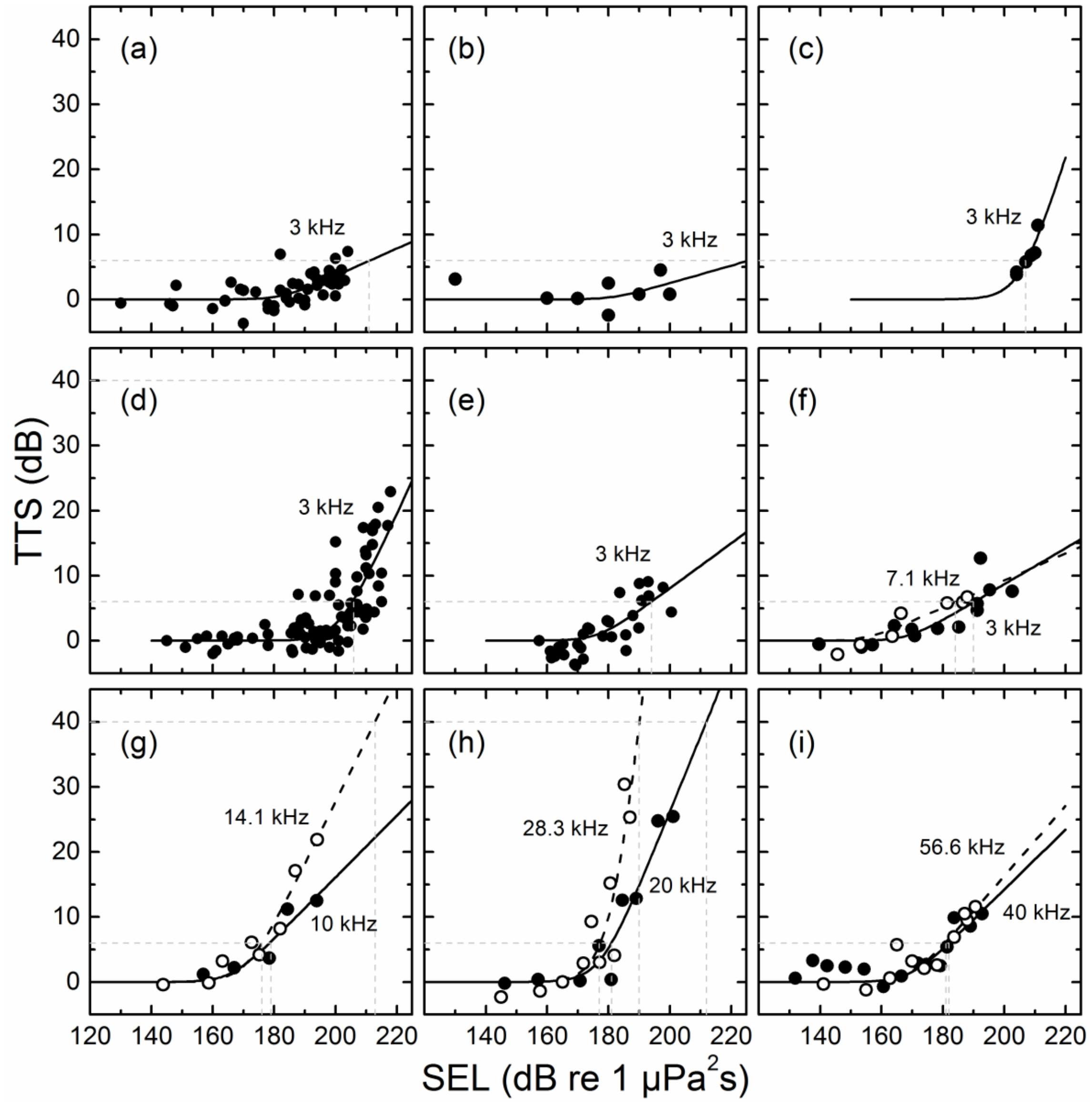

Figure 2-10. TTS growth data for mid-frequency cetaceans obtained using behavioral methods. Growth curves were obtained by fitting Eq. (10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table 2-6 for explanation of the datasets in each panel. Frequencies listed in each panel denote the exposure frequency.

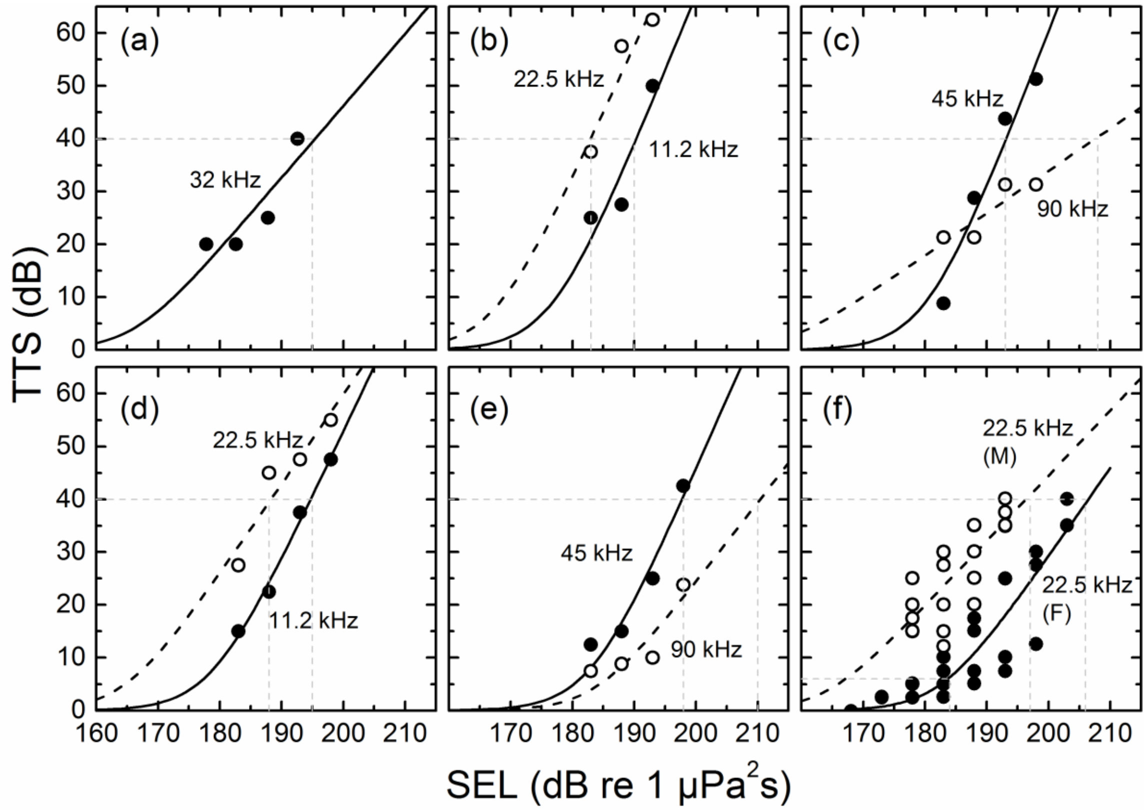

Figure 2-11. TTS growth data for mid-frequency cetaceans obtained using AEP methods. Growth curves were obtained by fitting Eq. (10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table 2-6 for explanation of the datasets in each panel.

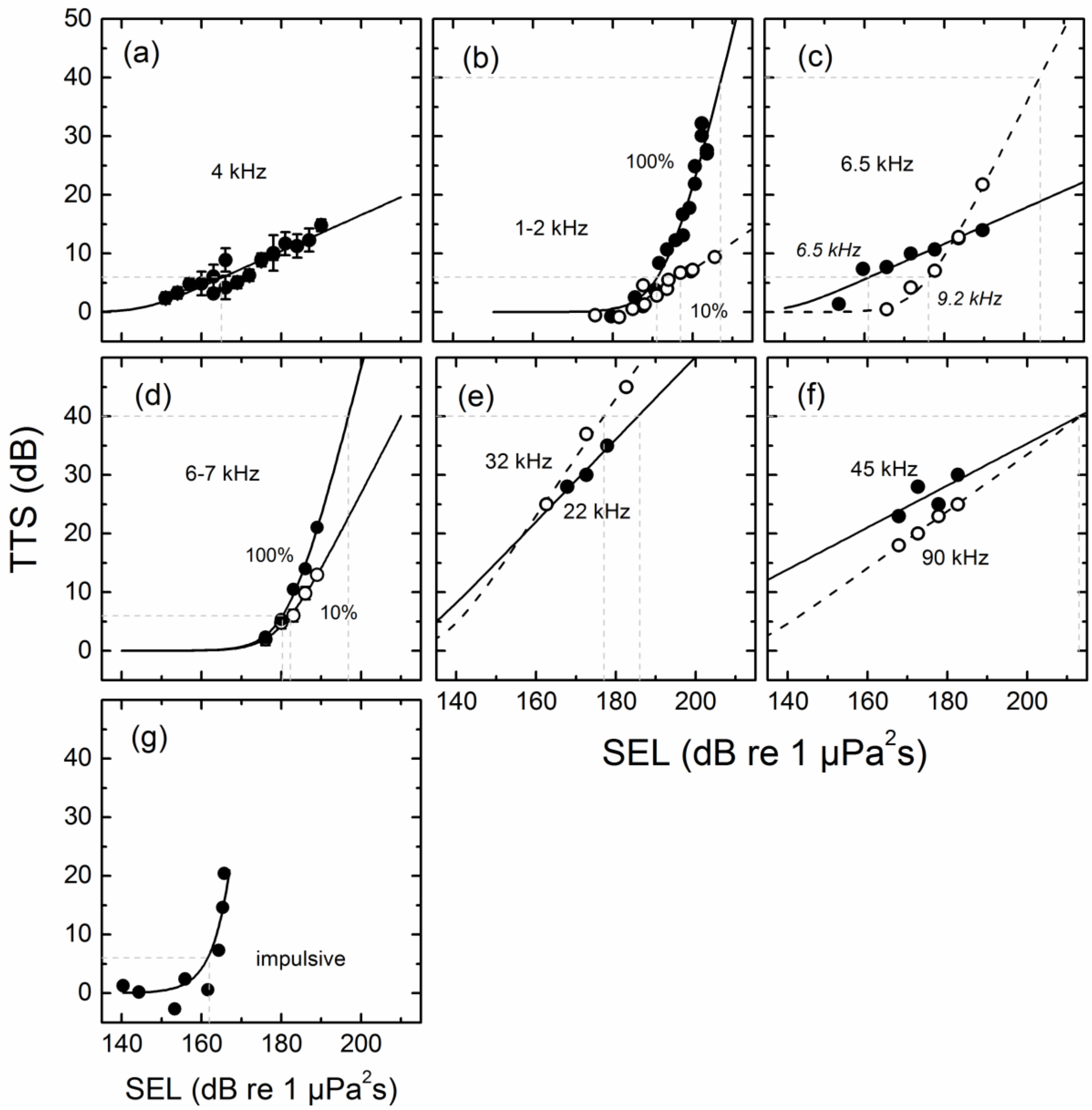

Figure 2-12. TTS growth data for high-frequency cetaceans obtained using behavioral and AEP methods. Growth curves were obtained by fitting Eq. (10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. The exposure frequency is specified in normal font; italics indicate the hearing test frequency. Percentages in panels (b), (d) indicate exposure duty cycle (duty cycle was 100% for all others). Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table 2-6 for explanation of the datasets in each panel.

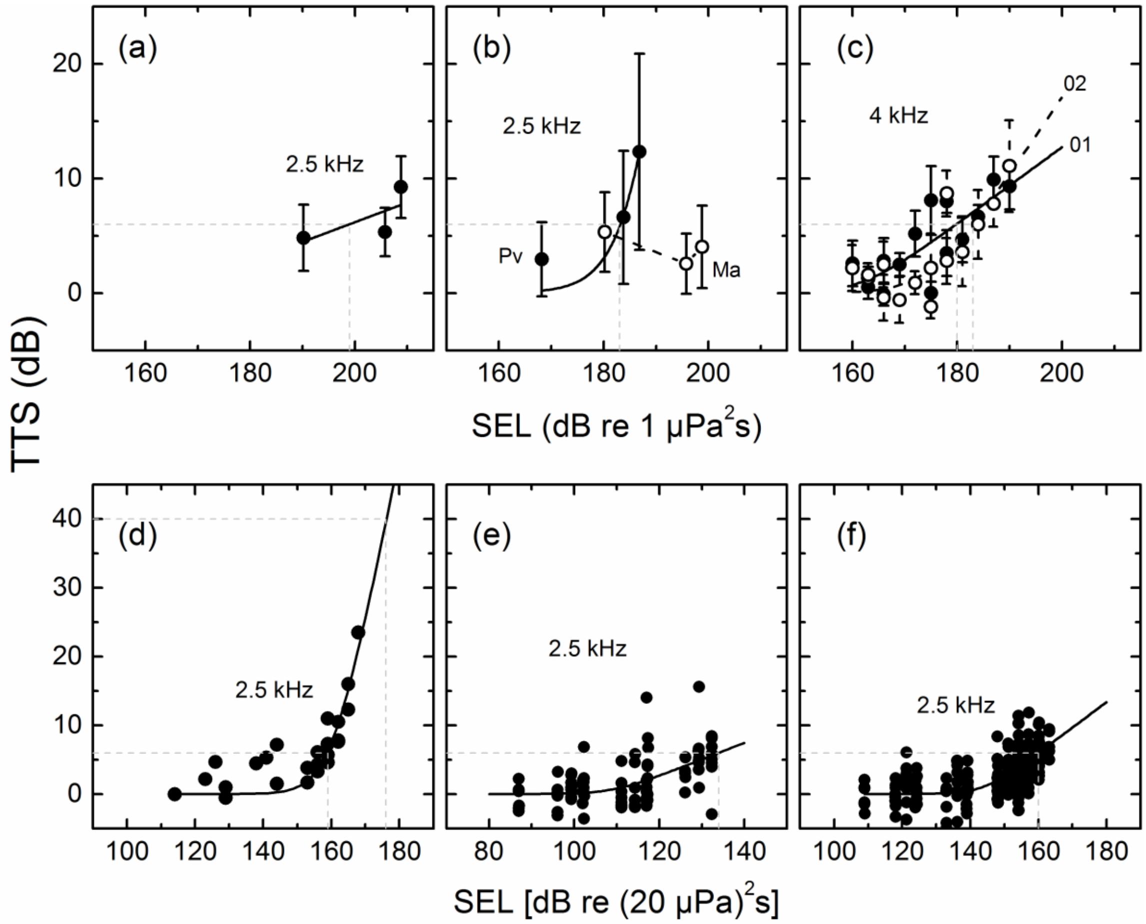

Figure 2-13. TTS growth data for pinnipeds obtained using behavioral methods. Growth curves were obtained by fitting Eq. (10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Numeric values in panel (c) indicate subjects 01 and 02. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See for Table 2-6 explanation of the datasets in each panel.

Table 2-6. Summary of marine mammal TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 μPa^{2}s underwater and dB re (20 μPa)^{2}s in air (groups OA and PA only). Tests featured continuous exposure to steady-state noise and behavioral threshold measurements unless otherwise indicated.

Group	*Species*	*Subject*	*Freq. (kHz)*	*Min TTS (dB)*	*Max TTS (dB)*	*TTS Onset (dB SEL)*	*TTS growth rate (dB/dB)*	*PTS Onset (dB SEL)*	*TTS-PTS offset (dB)*	*Notes*	*Reference*	*Figure*
MF	*Tursiops truncatus*	BEN	3	0	7	211*	0.21	—	—	TTS onset higher than subsequent test	(Finneran et al., 2005b)	2-10(a)
MF	*Tursiops truncatus*	NAY	3	0	5	—	0.13	—	—		(Finneran et al., 2005b)	2-10(b)
MF	*Tursiops truncatus*	BLU	3	4	11	207*	1.5	—	—	intermittent	(Finneran et al., 2010b)	2-10(c)
MF	*Tursiops truncatus*	BLU	3	0	23	206*	1.0	240	34	TTS onset higher than subsequent tests	(Finneran et al., 2010a)	2-10(d)
MF	*Tursiops truncatus*	TYH	3	0	9	194	0.35	—	—		(Finneran et al., 2010a)	2-10(e)
MF	*Tursiops truncatus*	BLU	3 7.1 10 14.1 20 28.3	0 0 1 0 0 0	13 7 13 22 25 30	190 184 179 176 181 177	0.28 0.21 0.48 0.95 1.2 4.5	— — — 213 212 190	— — — 37 31 13		(Finneran & Schlundt, 2013)	2-10(f) 2-10(f) 2-10(g) 2-10(g) 2-10(h) 2-10(h)
MF	*Tursiops truncatus*	TYH	40 56.6	0 0	11 12	182 181	0.46 1.1	— —	— —		(Finneran & Schlundt, 2013)	2-10(i) 2-10(i)

Group	***Species***	***Subject***	***Freq. (kHz)***	***Min TTS (dB)***	***Max TTS (dB)***	***TTS Onset (dB SEL)***	***TTS growth rate (dB/dB)***	***PTS Onset (dB SEL)***	***TTS-PTS offset (dB)***	***Notes***	***Reference***	***Figure***
MF	*Delphinapterus leucas*	N/a	32	20	40	—	1.4	195	—	AEP	(Popov et al., 2011a)	2-11(a)
MF	*Delphinapterus leucas*	female	11.2 22.5 45 90	25 38 9 21	50 63 51 31	— — — —	2.8 2.5 3.0 0.8	190 183 193 208	— — — —	AEP	(Popov et al., 2013)	2-11(b) 2-11(b) 2-11(c) 2-11(c)
MF	*Delphinapterus leucas*	male	11.2 22.5 45 90	15 28 13 8	48 55 42 24	— — — —	2.5 1.7 2.7 1.5	195 188 198 210	— — — —	AEP	(Popov et al., 2013)	2-11(d) 2-11(d) 2-11(e) 2-11(e)
MF	*Delphinapterus leucas*	female	22.5	0	40	184*	1.7	206	22	AEP	(Popov et al., 2014)	2-11(f)
MF	*Delphinapterus leucas*	male	22.5	12	40	—	1.2	197	—	AEP	(Popov et al., 2014)	2-11(f)
HF	*Phocoena phocoena*	02	4	2	15	165	0.3	—	—		(Kastelein et al., 2012b)	2-12(a)
HF	*Phocoena phocoena*	02	~1.5 ~1.5	0 0	32 7	191 197*	2.8 0.4	207 —	16 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2014b)	2-12(b) 2-12(b)
HF	*Phocoena phocoena*	02	6.5 6.5	1 0	13 22	161 176*	0.3 1.3	— 204	— 28	6.5 kHz test freq. 9.2 kHz test freq.	(Kastelein et al., 2014c)	2-12(c) 2-12(c)
HF	*Phocoena phocoena*	02	~6.5 ~6.5	2 2	21 13	180* 182*	2.7 1.3	197 —	17 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2015b)	2-12(d) 2-12(d)
HF	*Neophocaena phocaenoides*	male	22 32	28 25	35 45	— —	0.7 1.0	186 177	— —	AEP	(Popov et al., 2011b)	2-12(e)

Group	***Species***	***Subject***	***Freq. (kHz)***	***Min TTS (dB)***	***Max TTS (dB)***	***TTS Onset (dB SEL)***	***TTS growth rate (dB/dB)***	***PTS Onset (dB SEL)***	***TTS-PTS offset (dB)***	***Notes***	***Reference***	***Figure***
HF	*Neophocaena phocaenoides*	female	45 90	23 18	30 25	— —	0.36 0.48	213 213	— —	AEP	(Popov et al., 2011b)	2-12(f)
HF	*Phocoena phocoena*	Eigil	impulse	0	20	162	**	—	—	AEP	(Lucke et al., 2009)	2-12(g)
OW	*Zalophus californianus*	Rio	2.5	5	9	199	0.17	—	—		(Kastak et al., 2005)	2-13(a)
PW	*Phoca vitulina*	Sprouts	2.5	3	12	183	6.4	—	—		(Kastak et al., 2005)	2-13(b)
PW	*Mirounga angustirostris*	Burnyce	2.5	3	5	—	—	—	—		(Kastak et al., 2005)	2-13(b)
PW	*Phoca vitulina*	01	4	0	10	180	0.33	—	—		(Kastelein et al., 2012a)	2-13(c)
PW	*Phoca vitulina*	02	4	0	11	183*	0.68	—	—	TTS$_{16}$	(Kastelein et al., 2012a)	2-13(c)
OA	*Zalophus californianus*	Rio	2.5	0	24	159	2.4	176	17		(Kastak et al., 2007)	2-13(d)
PA	*Phoca vitulina*	Sprouts	2.5	0	16	134	0.24	—	—		(Kastak et al., 2004) (Kastak et al., 2005)	2-13(e)
PA	*Mirounga angustirostris*	Burnyce	2.5	0	12	160*	0.37	—	—		(Kastak et al., 2004)	2-13(f)

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

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

2.9 TTS Exposure Functions for Sonar

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

2.9.1 Low- and high-frequency exponents (a, b)

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

The low-frequency exponent, a, was defined as $a = s_0/20$, where s_0 is the lower of the slope of the audiogram or equal latency curves (in dB/decade) at low frequencies (Table 2-5). This causes the weighting function slope to match the shallower slope of the audiogram or equal latency contours at low frequencies. In practice, the audiogram slopes were lower than the equal latency slopes for all groups except the phocids, otariids, and other marine carnivores in air (groups OA and PA), and the mid-frequency cetaceans (group MF).

2.9.2 Frequency cutoffs (f_1, f_2)

The frequency cutoffs f_1 and f_2 were defined as the frequencies below and above the frequency of best hearing (f_0, Table 2-5) where the composite audiogram thresholds values were ΔT-dB above the threshold at f_0 (Figure 2-14). If $\Delta T = 0$, the weighting function shape would match the shape of the inverse audiogram. Values of $\Delta T > 0$ progressively “compress” the weighting function, compared to the audiogram, near the frequency region of best sensitivity. This compression process is included to match the marine mammal TTS data, which show less change in TTS onset with frequency than would be predicted by the audiogram in the region near best sensitivity.

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

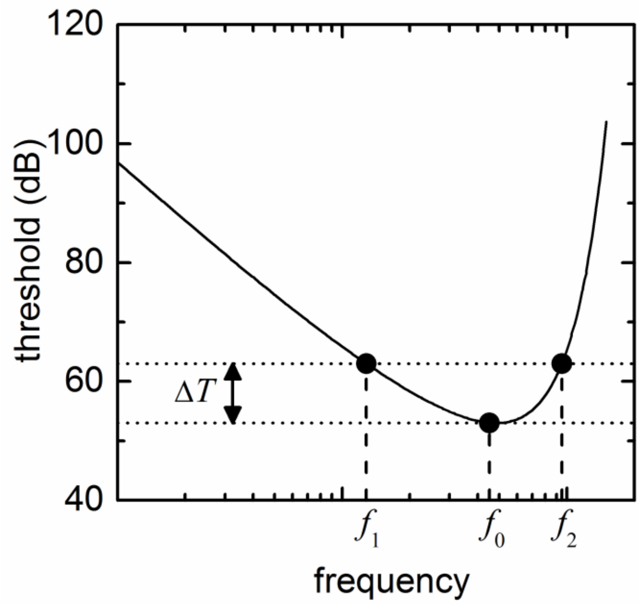

Figure 2-14. The cutoff frequencies f_1 and f_2 were defined as the frequencies below and above f_0 at which the composite audiogram values were ΔT-dB above the threshold at f_0 (the lowest threshold).

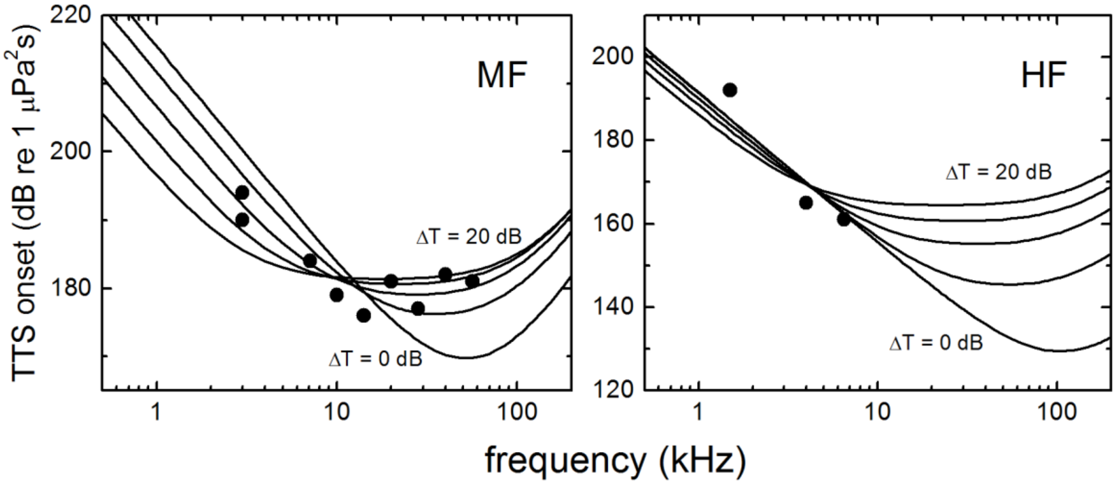

Figure 2-15. Effect of ΔT adjustment on the TTS exposure functions for the mid-frequency cetaceans (left) and high-frequency cetaceans (right). To calculate the exposure functions, a and b were defined as $a = s_0/20$ and $b = 2$. ΔT was then varied from 0 to 20. At each value of ΔT, K was adjusted to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

For the original and normalized data, the errors between the best-fit exposure functions and the TTS data for the MF and HF cetaceans were squared, summed, and divided by the total number of TTS data points

(12). This provided an overall mean-squared error (MSE) for the original and normalized data as a function of Δ*T* (Figure 2-16). The conditions (Δ*T* value and original/normalized threshold audiograms) resulting in the lowest MSE indicated the best fit of the exposure functions to the TTS data. For the MF and HF cetacean data, the lowest MSE occurred with the normalized threshold data with Δ*T* = 9 dB. *Therefore, f_1 and f_2 for the remaining species groups were defined using composite audiograms based on normalized thresholds with ΔT = 9 dB.*

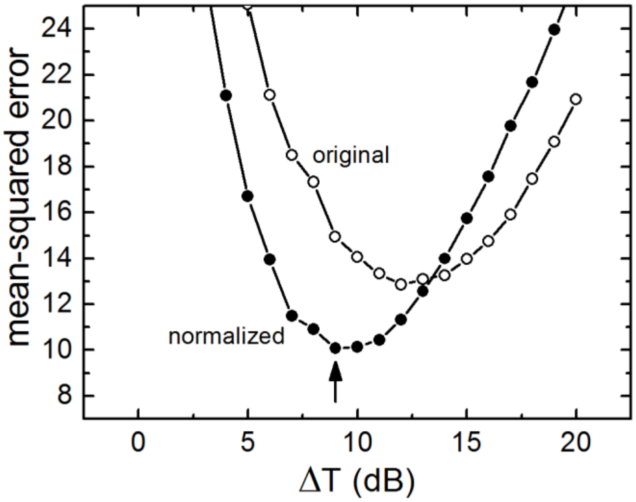

Figure 2-16. Relationship between Δ*T* and the resulting mean-squared error (MSE) between the exposure functions and onset TTS data. The MSE was calculated by adding the squared errors between the exposure functions and TTS data for the MF and HF cetacean groups, then dividing by the total number of TTS data points. This process was performed using the composite audiograms based on original and normalized threshold data and Δ*T* values from 0 to 20. The lowest MSE value was obtained using the audiograms based on normalized thresholds with Δ*T* = 9 dB (arrow).

2.9.3 Gain parameters *K* and *C*

The gain parameter *K* was defined to minimize the squared error between the exposure function and the TTS data for each species group. Note that *K* is not necessarily equal to the minimum value of the exposure function.

Because no TTS data exist low-frequency cetaceans and sirenians, TTS onset at the frequency of best hearing (f_0) was estimated by assuming that the numeric difference between the auditory threshold (in dB SPL) at the frequency of best hearing and the onset of TTS (in dB SEL) would be similar to that observed in the other species groups. Table 2-7 summarizes the onset TTS and composite threshold data for the MF, HF, OW, and PW groups. For these groups, the median difference between the TTS onset and composite audiogram threshold at f_0 was 126 dB. In the absence of data, the hearing threshold at f_0 for the LF group was set equal to the median threshold at f_0 for the in-water marine mammal groups (MF, HF, SI, OW, PW, median = 54 dB re 1 µPa). The TTS onset value at f_0 is therefore 180 dB re 1 µPa^{2}s for the low-frequency cetaceans (Table 2-7). For the sirenians, the lowest threshold was 61 dB re 1 µPa, making the onset TTS estimate 187 dB re 1 µPa^{2}s (Table 2-7).

Table 2-7. Differences between composite threshold values (Figure 2-5) and TTS onset values at the frequency of best hearing (f_0) for the in-water marine mammal species groups. The values for the low-frequency cetaceans and sirenians were estimated using the median difference (126) from the MF, HF, OW, and PW groups.

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

In contrast to the low-frequency cetaceans and sirenians, which are mammals and possess inner ears that are functionally analogous to those of the other marine mammals, sea turtle ears are anatomically different. Even within their best hearing range, sea turtles have low sensitivity, with lowest thresholds about 40 dB higher than those for mid-frequency cetaceans and audiograms more similar to those of fishes without specialized auditory adaptations for higher frequency hearing than to marine mammals. Considering these relationships, a working group (WG) established to determine sound exposure guidelines for fishes and sea turtles concluded (Popper et al., 2014):

Though there has been some discussion of using data from marine mammals to predict turtle responses, it is the view of the WG that, while still unsatisfactory, data from fishes provide a better analogy at this time. The rationale is that the hearing range for turtles much more approximates that of fishes than of any marine mammal, and the functioning of the basilar papilla in the turtle ear is dissimilar to the functioning of the cochlea in mammals.

For these reasons, the gain factor *K* for sea turtles was estimated using TTS data for fish rather than marine mammals. Using acoustic signals representative of low- and mid-frequency active sonar, Halvorsen et al. (2012; 2013) reported TTS in some, but not all, species of fish exposed to cumulative SELs of approximately 220 dB re 1 µPa^{2}s between 2 and 3 kHz and 210 to 215 dB re 1 µPa^{2}s between 170 and 320 Hz, respectively. Based on these data, Navy Phase III analyses used an SEL of 200 dB re 1 µPa^{2}s as an estimate for TTS onset in sea turtles at an exposure frequency of 200 Hz. Accordingly, the gain factor *K* was adjusted to set the minimum value of the TTS exposure function for sea turtles to 200 dB re 1 µPa^{2}s.

Once *K* was determined, the weighted threshold for onset TTS was determined from the minimum value of the exposure function. Finally, the constant *C* was determined by substituting parameters a, b, f_1, and f_2 into Eq. (1), then adjusting *C* so the maximum amplitude of the weighting function was 0 dB; this is equivalent to the difference between the weighted TTS threshold and *K* [see Eqs. (3)–(8)].

Table 2-8 summarizes the various function parameters, the weighted TTS thresholds, and the goodness of fit values between the TTS exposure functions and the onset TTS data. The various TTS exposure functions are presented in Figure 2-17Figure 2-20.

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

Group	*a*	*b*	*f_1 (kHz)*	*f_2 (kHz)*	*K (dB)*	*C (dB)*	*Weighted TTS threshold (dB SEL)*	*R^2*
LF	1	2	0.20	19	179	0.13	179	—
MF	1.6	2	8.8	110	177	1.20	178	0.825
HF	1.8	2	12	140	152	1.36	153	0.864
SI	1.8	2	4.3	25	183	2.62	186	—
OW	2	2	0.94	25	198	0.64	199	—
PW	1	2	1.9	30	180	0.75	181	0.557
TU	1.4	2	0.077	0.44	198	2.35	200	—
OA	1.4	2	2	20	156	1.39	157	—
PA	2	2	0.75	8.3	132	1.50	134	—

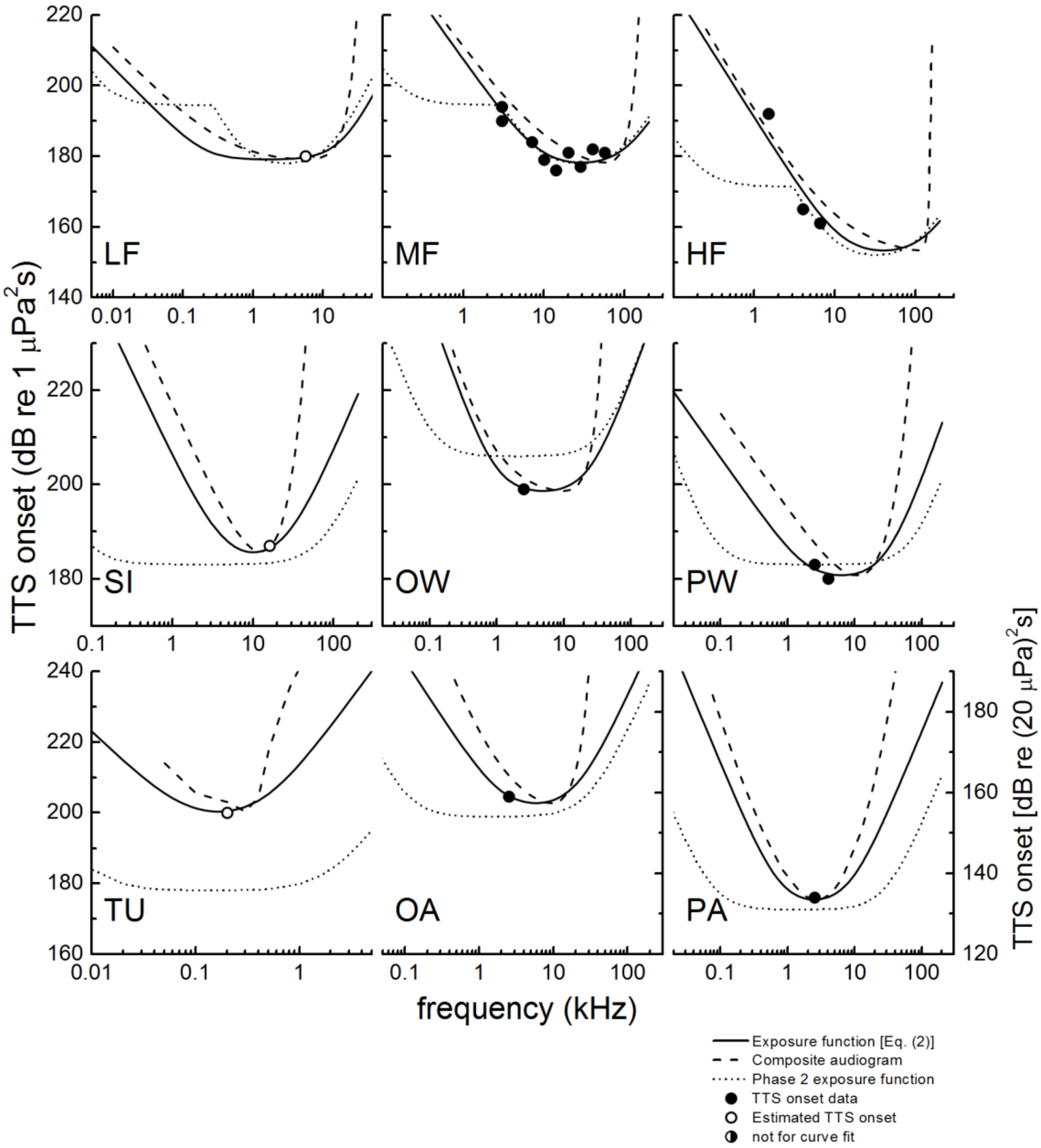

Figure 2-17. Exposure functions (solid lines) generated from Eq. (2) with the parameters specified in Table 2-7. Dashed lines — (normalized) composite audiograms used for definition of parameters *a*, f_1, and f_2. A constant value was added to each audiogram to equate the minimum audiogram value with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

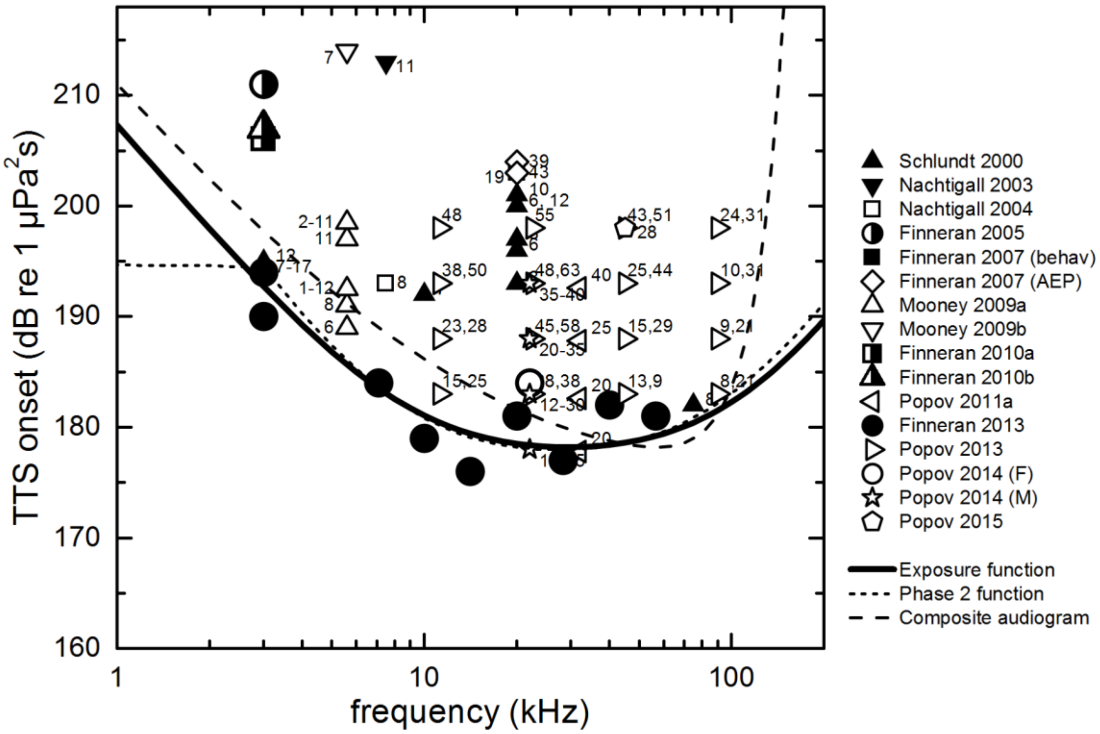

Figure 2-18. Mid-frequency cetacean exposure function, (normalized) composite audiogram, and Phase II exposure functions compared to mid-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric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

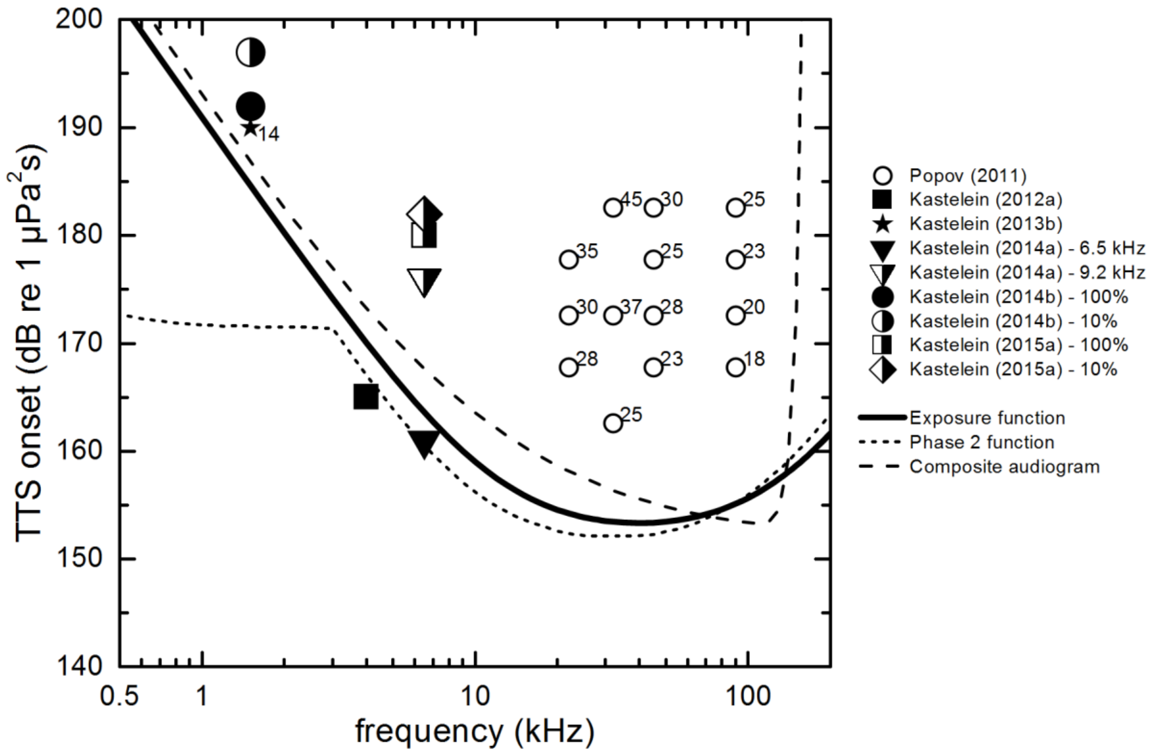

Figure 2-19. High-frequency cetacean TTS exposure function, (normalized) composite audiogram, and Phase II exposure functions compared to high-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with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

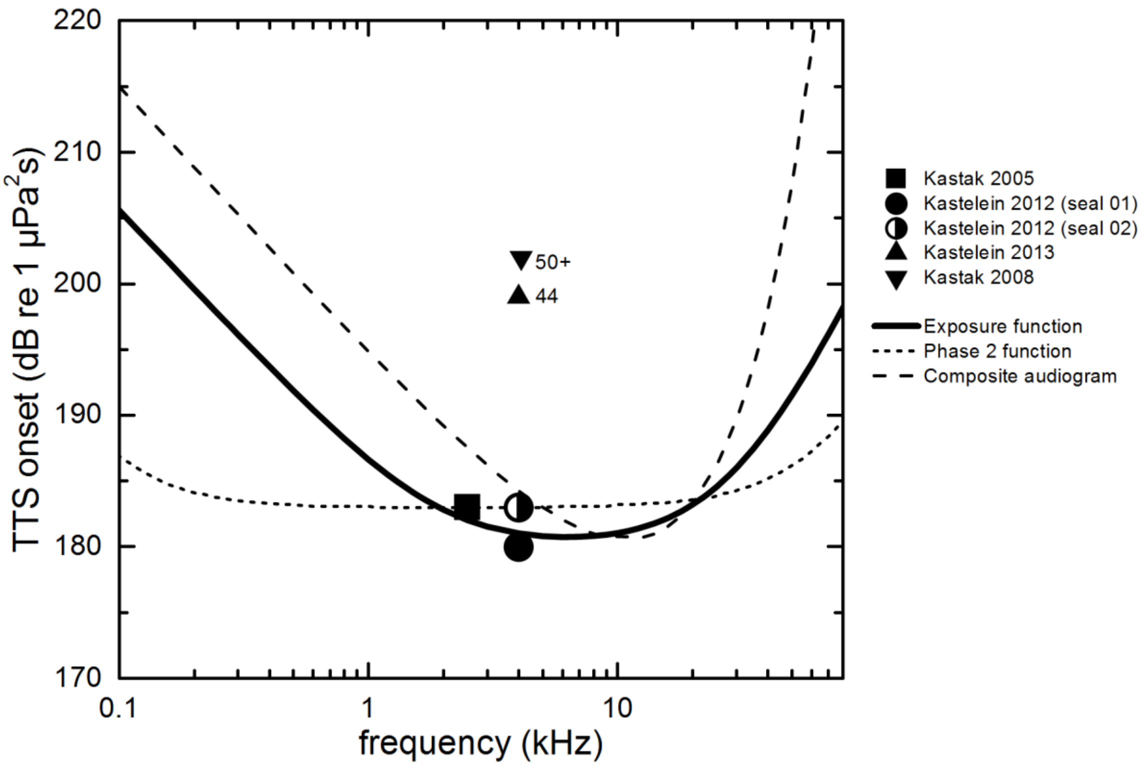

Figure 2-20. Phocid (underwater) exposure function, (normalized) composite audiogram, and Phase II exposure functions compared to phocid TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving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

2.10 PTS Exposure Functions for Sonar

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

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

For Phase III, a difference of 20 dB between TTS onset and PTS onset is used for all species groups. This is based on estimates of exposure levels actually required for PTS (i.e., 40 dB of TTS) from the marine mammal TTS growth curves (Table 2-6), which show differences of 13 to 37 dB (mean = 24, median = 22, *n* = 9) between TTS onset and PTS onset in marine mammals. These data show most differences between TTS onset and PTS onset are larger than 20 dB and all but one value are larger than 14 dB.

The value of *K* for each PTS exposure function and the weighted PTS threshold are therefore determined by adding 20 dB to the *K*-value for the TTS exposure function or the TTS weighted threshold, respectively (see Table C.2 in Appendix C).

2.11 TTS/PTS Exposure Functions for Explosives

The shapes of the TTS and PTS exposure functions for explosives and other impulsive sources are identical to those used for sonar and other transducers (i.e., steady-state or non-impulsive noise sources). Thus, defining the TTS and PTS functions only requires the values for the constant *K* to be determined.

Phase III analyses for TTS and PTS from underwater detonations and other impulsive sources follow the approach proposed by Southall et al. (2007) and used in Phase II analyses (Finneran & Jenkins, 2012a), where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold. The threshold producing the greater range for effect is used for estimating the effects of the noise exposure.

Peak SPL and SEL thresholds for TTS were based on TTS data from impulsive sound exposures that produced 6 dB or more TTS for the mid- and high-frequency cetaceans (the only groups for which data are available). The peak SPL thresholds were taken directly from the literature: 224 and 196 dB re 1 µPa, for the mid- and high-frequency cetaceans, respectively (Table 2-9). The SEL-based thresholds were determined by applying the Phase III weighting functions for the appropriate species groups to the exposure waveforms that produced TTS, then calculating the resulting weighted SELs. When this method is applied to the exposure data from Finneran et al. (2002) and Lucke et al.(2009), the SEL-based weighted TTS thresholds are 170 and 140 dB re 1 µPa^{2}s for the mid- and high-frequency cetaceans, respectively (Table 2-9). Note that the data from Lucke et al. (2009) are based on AEP measurements and may thus under-estimate TTS onset; however, they are used here because of the very limited nature of the impulse TTS data for marine mammals and the likelihood that the high-frequency cetaceans are more susceptible than the mid-frequency cetaceans (i.e., use of the mid-frequency cetacean value is not appropriate). Based on the limited available data, it is reasonable to assume that the exposures described by Lucke et al.(2009), which produced AEP-measured TTS of up to 20 dB, would have resulted in a behavioral TTS of at least 6 dB.

The harbor porpoise data from Kastelein et al. (2015a) were not used to derive the high-frequency cetacean TTS threshold, since the largest observed TTS was only 4 dB. However, these data provide an opportunity to check the TTS onset proposed for the high-frequency cetacean group. Kastelein et al. (2015a) provide a representative frequency spectrum for a single, simulated pile driving strike at a specific measurement location. When the high-frequency cetacean weighting function is applied to this spectrum and the 1/3-octave SELs combined across frequency, the total weighted SEL for a single strike is found to be 114 dB re 1 µPa^{2}s. For 2760 impulses, the cumulative, weighted SEL would then be 148 dB re 1 µPa^{2}s. The average SEL in the pool was reported to be 9 dB lower than the SEL at the measurement position, thus the average, cumulative weighted SEL would be approximately 139 dB re 1 µPa^{2}s, which compares favorably to the high-frequency cetacean TTS threshold of 140 dB re 1 µPa^{2}s derived from the Lucke et al. (2009) airgun data.

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

$$G_s - G_i = \overline{C_s} - \overline{C_i}, \quad (11)$$

where G indicates thresholds for a species group for which impulse TTS data are not available, $\overline{C}$ indicates the median threshold for the groups for which data exist, the subscript *s* indicates a steady-state threshold, and the subscript *i* indicates an impulse threshold (note that since data are only available for the mid- and high-frequency cetaceans the median and mean are identical). Equation (11) is equivalent to the relationship used by Southall et al. (2007), who expressed the relationship as $\overline{C_s} - G_s = \overline{C_i} - G_i$. For the mid- and high-frequency cetaceans, the steady-state TTS thresholds are 178 and 153 dB re 1 μPa²s (Table 2-8), respectively, and the impulse TTS thresholds are 170 and 140 dB re 1 μPa²s (Table 2-9), respectively, making $\overline{C_s} - \overline{C_i}$ = 11 dB. Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 11 dB below the steady-state TTS threshold (Table 2-9).

To estimate peak SPL-based thresholds, Southall et al. (2007) used Eq. (11) with peak-SPL values for the impulse thresholds and SEL-based values for the steady-state thresholds. For the mid- and high-frequency cetaceans, the steady-state (SEL) TTS thresholds are 178 and 153 dB re 1 μPa²s, respectively, and the peak SPL, impulse TTS thresholds are 224 and 196 dB re 1 μPa, respectively, making $\overline{C_s} - \overline{C_i}$ = -44 dB. Based on this relationship, the peak SPL-based impulse TTS threshold (in dB re 1 μPa) would be 44 dB above the steady-state TTS threshold (in dB re 1 μPa²s), making the peak SPL thresholds vary from 222 to 243 dB re 1 μPa. Given the limited nature of the underlying data, and the relatively high values for some of these predictions, for Phase III analyses impulsive peak SPL thresholds are estimated using a "dynamic range" estimate based on the difference (in dB) between the impulsive noise, peak SPL TTS onset (in dB re 1 μPa) and the hearing threshold at f_0 (in dB re 1 μPa) for the groups for which data are available (the mid- and high-frequency cetaceans). For the mid-frequency cetaceans, the hearing threshold at f_0 is 54 dB re 1 μPa and the peak SPL TTS threshold is 224 dB re 1 μPa, resulting in a dynamic range of 170 dB. For the high-frequency cetaceans, the hearing threshold at f_0 is 48 dB re 1 μPa and the peak SPL-based TTS threshold is 196 dB re 1 μPa, resulting in a dynamic range of 148 dB. The median dynamic range for the mid- and high-frequency cetaceans is therefore 159 dB (since there are only two values, the mean and median are equal). For the remaining species groups, the impulsive peak SPL-based TTS thresholds are estimated by adding 159 dB to the hearing threshold at f_0 (Table 2-9).).

There are no published data regarding TTS in sea turtles exposed to underwater explosions or other impulsive noise sources. As a conservative approach, Popper et al. (2014) recommended applying impact thresholds developed for fishes without swim bladders to sea turtles. For fish without swim bladders, Popper et al. (2014) recommended SEL-based thresholds >> 186 dB re 1 μPa²s for TTS after exposure to impact pile driving or seismic airgun impulses. For marine mammals, an 11-dB difference was found between the SEL-based non-impulsive TTS threshold and the SEL-based impulsive TTS threshold. If this same rule is applied to sea turtles, the SEL-based, impulse TTS threshold would be 189 dB re 1 μPa²s (non-impulsive TTS threshold of 200 dB re 1 μPa²s less 11 dB) — slightly higher than the fish threshold of 186 dB re 1 μPa²s. Popper et al. (2014) make no recommendations for peak SPL-based TTS thresholds for sea turtles. Given the high hearing thresholds measured for sea turtles and the relatively high SEL-based TTS thresholds, it seems likely that the peak SPL-based threshold for sea turtles would be higher than that for marine mammals. Based on this, the Phase III sea turtle peak SPL-based TTS threshold for impulse noise is set to 226 dB re 1 μPa, to match the highest marine mammal value.

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

Table 2-9. TTS and PTS thresholds for explosives and other impulsive sources. SEL thresholds in dB re 1 μPa^{2}s underwater and dB re (20 μPa)^{2}s in air (groups OA and PA only). Peak SPL thresholds in dB re 1 μPa underwater and dB re 20 μPa in air (groups OA and PA only).

Group	*Hearing threshold at f_0*	*TTS threshold*		*PTS threshold*	
	SPL (dB SPL)	*SEL (weighted) (dB SEL)*	*peak SPL (dB SPL)*	*SEL (weighted) (dB SEL)*	*peak SPL (dB SPL)*
LF	54	168	213	183	219
MF	54	170	224	185	230
HF	48	140	196	155	202
SI	61	175	220	190	226
OW	67	188	226	203	232
PW	53	170	212	185	218
TU	95	189	226	204	232
OA	11	146	170	161	176
PA	-4	123	155	138	161

3 NAVY PHASE III BEHAVIORAL RESPONSE CRITERIA FOR MARINE SPECIES

3.1 Sonar and Other Transducers

3.1.1 Introduction

This section outlines the criteria used in Navy Phase III analyses to predict behavioral effects to marine mammals from sonar and other transducers. Recent behavioral studies have provided new data on how some species of marine mammals react to activities utilizing sonar and similar sound sources. Multi-year research efforts in the United States and Norway have conducted sonar exposure studies in the field on wild odontocetes and mysticetes (DeRuiter et al., 2013; Goldbogen et al., 2013; Miller et al., 2012; Sivle et al., 2012). Several studies with captive animals have provided data under controlled circumstances for odontocetes and pinnipeds (Houser et al., 2013a, 2013b). Finally, Moretti et al. (2014) published a beaked whale dose-response curve based on passive acoustic monitoring of beaked whales during U.S. Navy training activity at Atlantic Underwater Test and Evaluation Center (AUTEC) during actual Anti-Submarine Warfare exercises. This new information has necessitated the update of the Navy's behavioral response criteria.

Sea turtle behavioral criteria was developed with the National Marine Fisheries Service (NMFS), and is briefly discussed in Section 3.1.8.9 (Sea Turtles under Behavioral Response Functions and Thresholds for Sonar and Other Transducers) and Section 3.1.9.7 (Sea Turtles under the Application of Contextual Factors – Distance Cutoffs).

3.1.2 Significant Behavioral Responses

In this report, the terms 'significant response' or 'significant behavioral response' are used in describing behavioral observations from field or captive animal research that may rise to the level of 'harassment' under the MMPA for military readiness activities. Due to the nature of behavioral response research to date, it is not currently possible to ascertain the number of these observed significant reactions that would lead to an abandonment or significant alteration of a natural behavior pattern as a result of naval activities.

Under the Marine Mammal Protection Act, for military readiness activities, such as Navy training and testing, behavioral 'harassment' is:

"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*." (Section 315(f) of Public Law 107–314; 16 U.S.C. 703 note)

Behavioral response severity is described herein as low, moderate, or high. These are derived from the Southall et al. (2007) severity scale.

Low severity responses are within an animal's range of typical (baseline) behaviors and are unlikely to disrupt an individual to a point where natural behavior patterns are significantly altered or abandoned. Low severity responses include:

- Orientation response
- Startle response
- Change in respiration
- Change in heart rate
- Change in group spacing or synchrony

Moderate severity responses could become significant if sustained over a longer duration. What constitutes a long-duration response is different for each situation and species, although it is likely dependent upon the magnitude of the response and species characteristics such as body size, feeding strategy, and behavioral state at the time of the exposure. In general, a response would be considered 'long-duration' if it lasted for a few tens of minutes to a few hours, or enough time to significantly disrupt an animal's daily routine.

Moderate severity responses include:

- Alter migration path
- Alter locomotion (speed, heading)
- Alter dive profiles
- Stop/alter nursing
- Stop/alter breeding
- Stop/alter feeding/foraging
- Stop/alter sheltering/resting
- Stop/alter vocal behavior
- Avoidance of area near sound source
- Displays of aggression or annoyance (e.g., tail slapping)

Moderate severity responses would not be considered significant behavioral responses if they lasted for a short duration and the animal immediately returned to their pre-response behavior. Moderate severity responses would be considered significant behavioral responses if they were sustained for a long duration. For the derivation of behavioral criteria in this report, a long duration was defined as a response that lasted for the duration of exposure or longer, regardless of how long that may have been. This assumption was made because examination of behavioral response data suggests that had the exposure continued, the behavioral responses would have continued as well.

High severity responses are those with possible immediate consequences to growth, survivability, or reproduction:

- Long-term or permanent abandonment of area
- Prolonged separation of females and dependent offspring
- Panic, flight, or stampede
- Stranding

High severity responses include those with immediate consequences (e.g., stranding) and those affecting animals in vulnerable life stages (i.e., calf, pup, or cub), and are therefore always considered to be a significant behavioral reaction.

A number of behavioral experiments have been conducted with animals under human care to estimate received sound levels that lead to disturbance of either normal or trained behaviors. Equating behavioral responses of animals under human care to those in the wild is inherently difficult as the context of the experiment, history of behavioral conditioning, and the nature of the environment cannot be easily equated to natural settings, nor can it be easily determined if these conditions make animals more or less sensitive to the disturbance imposed. Nevertheless, studies with captive animals provide greater control over the sound exposure context and greater opportunity for observation. Thus, alignments between the severity of reaction between wild animals and those under human care have been proposed (Southall et al., 2007). The proposed alignment of reaction severities has been modified for this analysis. General examples of low severity behavioral responses in captive animals include:

- Brief changes in swim direction or orientation relative to sound source
- Small changes in respiration rates

General examples of moderate to high severity behavioral responses in captive animals include:

- Annoyance behavior (e.g., tail slapping, breaching, jaw-popping, chuffing)
- Refusal to participate
- Aggressive behavior
- Moderate to prolonged avoidance of the sound source
- Loss of behavioral control

3.1.3 Review of Phase II Behavioral Criteria

In Navy acoustic impact analyses during Phase II, the likelihood of behavioral effects to sonar and other transducers was based on a probabilistic function (termed a behavioral response function – BRF), that related the likelihood (i.e., probability) of a behavioral response to the received SPL (SPL). The BRF was used to estimate the percentage of an exposed population that is likely to exhibit altered behaviors or behavioral disturbance at a given received SPL. This BRF relied on the assumption that sound poses a negligible risk to marine mammals if they are exposed to SPL below a certain "basement" value. Above the basement exposure SPL, the probability of a response increased with increasing SPL.

Two BRFs were used in Navy acoustic impact analyses: BRF_1 for mysticetes and BRF_2 for other species (**Figure 3-1**). The BRFs were based on three sources of data: behavioral observations during TTS experiments conducted at the U.S. Navy Marine Mammal Program (Finneran & Schlundt, 2004); reconstruction of sound fields produced by the USS Shoup associated with the behavioral responses of killer whales observed in Haro Strait (Fromm, 2009; U.S. Department of the Navy, 2003); and observations of the behavioral response of North Atlantic right whales exposed to alert stimuli containing mid-frequency components (Nowacek et al., 2004a).

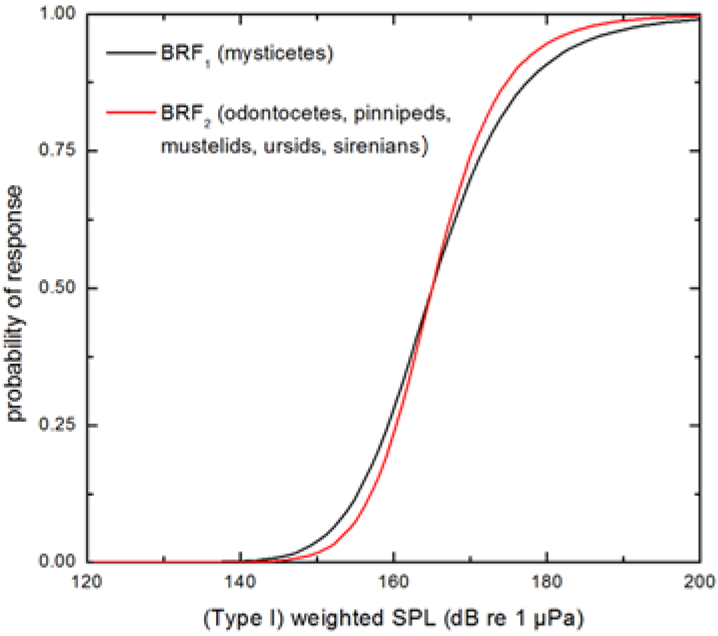

Figure 3-1. Phase II Navy Behavioral Response Functions.

BRFs were not used for harbor porpoises and beaked whales during Phase II analyses. Instead, a step function at an SPL of 120 dB re 1 µPa was used for harbor porpoises as a threshold to predict behavioral disturbance. Threshold levels at which both captive (Kastelein et al., 2000; Kastelein et al., 2005a) and wild harbor porpoises (Johnston, 2002) responded to sound (e.g., acoustic harassment devices, acoustic deterrent devices, or other non-impulsive sound sources) was very low, ranging between 100 and 145 dB re 1 µPa.

Results from Blainville's beaked whale monitoring and experimental exposure studies on the instrumented Atlantic Undersea Test and Evaluation Center range in the Bahamas (McCarthy et al., 2011; Tyack et al., 2011) suggested that beaked whales tended to avoid both actual naval mid-frequency sonar in real anti-submarine training scenarios as well as sonar-like signals and other signals used during controlled sound exposure studies in the same area. During an exercise using mid-frequency sonar, beaked whales avoided the area at a distance from the sonar where the received level was "around 140 dB" [dB re 1 µPa] and once the exercise ended, beaked whales returned to the center of exercise area within 2-3 days (Tyack et al., 2011). The Navy therefore adopted a 140 dB re 1 µPa SPL threshold for behavioral effects for all beaked whales (family: Ziphiidae) for the Phase II analysis.

3.1.4 Overview of the approach for Phase III

The Navy's at-sea environmental compliance program assesses training and testing activities over multi-year periods for each Fleet Area of Operations (AO), which can cover several hundred thousand square miles of ocean. Training and testing activities are numerous, with thousands of events per year for the Navy Study Areas. These events are analyzed over multiple areas and seasons to predict the potential impact of Navy testing and training activities on the marine environment. Criteria are developed to provide an estimate of potentially significant behavioral impacts using available data.

Developing the new behavioral criteria for Phase III involved multiple steps:

- All available behavioral response studies conducted both in the field and on captive animals were examined in order to understand the breadth of behavioral responses of marine mammals to sonar and other transducers. An overview of the literature considered for analysis is given in Section 3.1.5, along with details on the various sound sources used in each study.
- Marine mammal species were placed into behavioral criteria groups based on their known or suspected behavioral sensitivities to sound. In most cases these divisions are driven by taxonomic classifications (e.g., mysticetes, pinnipeds), as described in Section 3.1.6.
- Section 3.1.7 describes the differences between level-based and context-based behavioral responses to anthropogenic noise.
- The data from the behavioral studies were analyzed by looking for significant responses, or lack thereof, for each experimental session following definitions in Section 3.1.2. For groups that did not have adequate behavioral response data (i.e., sirenians), a surrogate BRF based on behavioral characteristics and taxonomy was assigned. Details are in Section 3.1.8.
- Distances beyond which significant behavioral responses to sonar and other transducers are unlikely to occur, denoted as "cutoff distances," were defined based on the existing data (see Section 3.1.8.9).
- Section 3.2 presents a summary of the behavioral criteria, examples of the effect of using cutoff distances, and a comparison of Phase II and Phase III behavioral criteria.

3.1.5 Review of Data Considered

A number of papers on behavioral responses of marine mammals to sonar or sonar-like sound sources have been published over the last few years. These recent studies, along with several previously published reports with behavioral response observations (Fromm, 2009) were considered when deriving the Navy's behavioral response criteria.

3.1.5.1 Behavioral Response Field Studies

Behavioral response field studies seek data under more realistic scenarios (as compared to a controlled laboratory setting); however, field experiments are unable to control all variables that are likely mediating behavioral responses. These other variables are often referred to as contextual factors (see Section 3.1.7 for more details). At moderate to lower received levels the correlation between probability of reaction and received level is very poor and it appears that other variables are mediating behavioral reactions. Contextual factors that are likely to have mediated responses during the behavioral response studies discussed below include: close proximity of the vessel and sound source, physical contact (i.e., tagging), repeated close approaches (within a few hundred meters), multiple vessels, and confined areas (i.e., fjords). Table 3-1describes the experimental conditions for each study in which data were used for the derivation of the Navy's Phase III behavioral response criteria.

Table 3-1. Description of experimental conditions used in behavioral response field studies included in the derivation of Phase III behavioral response thresholds.

Study	***Signal***	***Signal Frequency***	***Signal Duration***	***Signal Interval***	***Source Level (dB re 1 µPa @ 1 m)***	***Ship movement***	***Ship Distance***	***Exposure Session Duration***
SURTASS LFA[1]	LFA Sonar	Various 100-500 Hz tones/sweeps	< 50 sec	6 – 10 min	160-210	Approaching and stationary	Variable	2-3 hours
RW Alarm[2]	Alarm	500/800 Hz tones, 500-4500 sweep, 1500/2000 Hz AM tones	1-2 sec	72 sec	173 (max)	Slow Movement	NA	18 min
3S[3]	Sonar	6-7 kHz hyperbolic upsweep	1 sec	20 sec	158-199	Approaching	7-8 km to < 1 km	Variable ~30-60 min
3S[3]	Sonar	1-2 kHz hyperbolic upsweep	1 sec	20 sec	152-214	Approaching	7-8 km to < 1 km	Variable ~30-60 min
3S[3]	Sonar	1-2 kHz hyperbolic downsweep	1 sec	20 sec	152-214	Approaching	7-8 km to < 1 km	Variable ~30-60 min
AUTEC BRS[4]	Simulated Sonar	3.2-3.75 kHz sweep/tone	1.4 sec	25 sec	152-212	Stationary	1 km	~ 15 min
AUTEC BRS[4]	Pseudo-Random noise	3.2-3.75 kHz band	1.4 sec	25 sec	152-212	Stationary	1 km	~ 15 min
SOCALSOCAL BRS[5]	Simulated Sonar	3.5-4.05 kHz sweep/tone	1.6 sec	25 sec	160-210	Stationary	1 km	30 min
SOCALSOCAL BRS[5]	Pseudo-Random noise	3.5-4.05 kHz band	1.4 sec	25 sec	160-206	Stationary	1 km	30 min

[1](Tyack et al., 2011); [2](Nowacek et al., 2004a); [3](Miller et al., 2011); [4](Tyack et al., 2011); [5](Southall et al., 2012)

3.1.5.1.1 SURTASS LFA SRP

Studies of behavioral responses to low frequency sonar were undertaken in 1997–98 as part of the Navy's Low-Frequency Sound Scientific Research Program. The SURTASS LFA exposure studies on blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*), gray (*Eschrichtius robustus*), and humpback whales (*Megaptera novaeangliae*) (Croll et al., 2001; Tyack, 1999) were conducted in three phases. These studies found only short-term responses to low-frequency sound by these mysticetes, including changes in vocal activity and avoidance of the source vessel (Clark & Fristrup, 2001; Croll et al., 2001; Fristrup et al., 2003; Miller et al., 2000; Nowacek et al., 2007).

The first phase of the study consisted of both "bottom-bounce" and "direct-path" exposures of LFA sonar on blue and fin whales in the SOCAL Bight. Focal follows on six fin whales and one blue whale were conducted during LFA exposures, and none showed a discernible response or variation in foraging activity (Croll et al., 2001). Croll et al. (2001) also reported on results looking at changes in distribution to look for large-scale avoidance effects. They concluded that changes in distribution were due to changes in food distribution not the occurrence of the LFA source.

During the second phase of the study, a stationary ship transmitting LFA sonar was positioned in the path of migrating gray whales along the coast of California; the ship was positioned either 2 km from shore (directly in the path of the migrating whales) or 4 km offshore. Many animals were observed avoiding the sound source by altering their route 500 – 2000 m around the sound source vessel when the vessel was directly in the path at the 2 km position, but far fewer avoidance responses were observed when the vessel was 4 km offshore. Responses were relatively short-term, low impact avoidance responses, which were not significant behavioral responses (see Section 3.1.2 for more details). This exemplifies a contextually driven response that appears to be mediated by the location of the source in the middle or edge of the animal's migration path as opposed to the received level. Researchers also noted that the whales showed a very strong and obvious avoidance response to the small boat attempting to tag the animals, including some animals that turned and swam away at high speed, thwarting all attempts at tagging this species during the study.

During the third part of the SURTASS LFA study, the LFA sonar was played in the vicinity of humpback whales on their breeding grounds in Hawaii. Singing males were the primary target, but all whales in the vicinity of the sonar were observed from ship- and land-based platforms to monitor non-acoustic responses. No responses were observed visually; of the 17 singing humpbacks that were exposed to the sonar, seven did not respond at all while ten ceased their vocalizations. However, only six of the ten cessations of song were attributable as responses to the LFA sonar; the other four singers stopped singing but then joined another singer or group of whales, which is a common behavior by singers in Hawaiian waters. Even the responses by the six whales that may have responded to LFA were considered to be within the standard deviation of all behavior, and were therefore not confidently scored as actual responses. Researchers also noted that some humpbacks singers that were approached with a small boat as possible focal-follow subjects avoided the vessel, or stopped singing.

Data from the first and third phases of the LFA study were used in the quantitative derivation of new behavioral response criteria. There was no received level data paired with individual behavioral observations available for the second phase of the LFA study; therefore, these data were not used in the quantitative derivation of new behavioral response criteria.

3.1.5.1.2 **Reactions of right whales to alarm sounds**

Nowacek et al. (2004a) developed an alarm signal to be deployed from ships in order to alert north Atlantic right whales (*Eubalaena glacialis*) to their presence and help avoid ship strikes. The alarm signal was 18 minute long with a 60% duty cycle and designed to "pique the mammalian auditory system with disharmonic signals spanning the whale's estimated hearing range" (Nowacek et al., 2004a). Digital acoustic recording tags (DTAGs) were first attached to animals to record received sounds and animal movement. Whales were allowed a recovery period of two dives. Playback commenced on the third foraging dive from the animal's last dive location and the boat slowly followed the animals based on their last known heading. Six whales were exposed to the alert stimulus, five whales were exposed to a silent control, seven whales were exposed to playbacks of right whale social vocalizations, and five whales were exposed to a vessel approach stimulus. Five of the six whales exposed to the alert signal responded, while none of the whales exposed to other scenarios responded. Animals that reacted prematurely ended foraging dives, swam at a shallow angle to the surface, and remained there exhibiting abnormal diving behavior for the duration of the exposure. The authors point out that this was a response to the signal itself and not to varying received levels; the levels from the vessel approach playbacks were similar with no observed reactions (Nowacek et al., 2004a).

This shows that the qualities of a sound besides received level (e.g., disharmonic frequency content) can mediate behavioral reactions. Prior encroachment and tagging, as well as the proximity of the sound source located presumably almost directly above the animal upon initial exposure could also have caused animals to react at lower received levels than in the absence of these additional stimuli.

These data were included in the derivation of the behavioral criteria.

3.1.5.1.3 **Haro Strait killer whales**

In May 2003, killer whales in Haro Strait, Washington exhibited behavioral reactions while the USS *Shoup* was in the vicinity and engaged in MFAS training. Sound fields modeled for the USS *Shoup* transmissions (Fromm, 2009; National Marine Fisheries Service, 2005; U.S. Department of the Navy, 2003) estimated a brief maximum mean received SPL of approximately 169 dB re 1 µPa (modeled maximum values ranged from 150 to 180 dB re 1 µPa) at the location of the killer whales during the closest point of approach between the animals and the vessel (2.5 km). The mean received level in the minutes prior to the closest point of approach was 144 dB re 1 µPa. The killer whales had been traveling north, parallel to the path of the USS *Shoup* but ahead of the vessel. As the vessel approached, the whales first turned south and began heading towards the ship, then moved closer to shore and began milling. After the USS *Shoup* passed and the sonar was turned off, the killer whales resumed their northward travel. During this exposure there were up to six whale watching vessels surrounding the whales; at the time they turned south, most of the vessels were ahead of the group and possibly blocked their path. In addition, the estimated source levels of the surrounding whale watching vessels were between 145 and 169 dB re 1 µPa. The received levels of the whale watch boats' engine noise may have been high enough to mask the initial sound of the sonar as the USS *Shoup* approached the group of whales. Additionally, other research has shown that resident killer whales behaviorally respond to whale watching vessels at close ranges (Erbe, 2002; Williams et al., 2014). Finally, observers at the time of the exposure felt that the killer whales' behavior was not normal; however, researchers that later reviewed the video of the animals determined that their behavior during the exposure was within their normal behavioral range.

Data from this incidental exposure of resident killer whales were used in the development of the Phase II BRFs. However, due to a lack of paired data on observed reactions at specific received sound levels, these data were not used in the quantitative derivations of the new behavioral response criteria. Additionally, the 3S behavioral response study recorded detailed observations of killer whales reactions to sonar and therefore provides a better data set for the derivation of behavioral response criteria.

3.1.5.1.4 3S study

Miller et al. (2011) reported on behavioral responses of pilot whales (*Globicephala melas*), killer whales (*Orcinus orca*), and sperm whales (*Physeter macrocephalus*) off Norway to a Norwegian Navy sonar (Sea Mammals, Sonar, and Safety Project [3S]) (Antunes et al., 2014; Kuningas et al., 2013; Miller et al., 2014; Miller et al., 2012; Sivle et al., 2012). The sonar outputs included 1 - 2 kHz up- and down-sweeps and 6 - 7 kHz up-sweeps; source levels were ramped-up from 152 - 158 dB re 1µPa @ 1m to a maximum of 198 - 214 dB re 1µPa @ 1m.

After an initial observation period, but prior to sound exposure, researchers attached DTAGs to one or two of the animals in a selected group. Researchers spent up to one hour attaching recording tags to the animal(s), and multiple attempts at tag attachment were made during that period. Agitated behaviors from some animals were observed during the tagging process (Miller et al., 2011). After a period of twenty minutes to several hours following tag attachment, during which an observation vessel remained with the tagged animal(s), researchers began playbacks of sonar signals, playbacks of sounds made by feeding killer whales, or conducted silent “control” passes of the sonar vessel. At the start of an exposure session, the vessel with the active sonar source began approaching the group from 6 - 8 km and continued to vector towards the group until within approximately 1 km. The source vessel would then continue upon a straight course until it passed the animal group, often to within a few hundred meters. Many of the observed behavioral responses were of a prolonged duration, as the animals continued moving to avoid the oncoming vessel as it corrected course toward the animals. At the onset of each sonar exposure session, the signal amplitude was ramped-up over several pings while the vessel approached the animals. This rapid increase in received levels of subsequent sonar pings during ramp-up could have been perceived by the animals as a rapidly approaching source.

Three of the four exposed killer whale groups were foraging prior to the initial sonar exposure; they all ceased to feed and began avoiding the vessel during the first exposure session. Received SPLs corresponding to observed significant behavioral reactions varied from approximately 94 dB re 1 µPa at 8.9 km to 164 dB re 1 µPa at 3.2 km. The killer whale group that was not foraging was in a shallow part of the fjord and could only be approached to within about 2 km by the vessel towing the sonar source. Received SPLs in that case were as high as 166 dB re 1µPa with no observed reactions. This group did not respond to any of the exposures until the final approach, when the group had moved out of the shallow part of the fjord and a young calf became separated from the rest of the group.

Pilot whale behavioral responses occurred at received SPLs between approximately 152 to 175 dB re 1 µPa corresponding to distances of 3.1 km to 90 m, respectively; although during exposures as high as approximately 172 dB re 1 µPa corresponding to a distance of 350 m, no more than minor and brief reactions were observed.

Sperm whales responded at received levels between 116 to 156 dB re 1 µPa, corresponding to distances of around 9.0 to 1.8 km, respectively. However, sperm whales exposed to higher levels (up to 166 dB re 1 µPa at 0.9 km) showed no response, or no more than a brief and minor response. These counterintuitive results with respect to received SPL demonstrate some of the issues that must be addressed when interpreting behavioral response data for marine mammals in different contextual conditions.

The 3S study included some control passes of ships with the sonar off to discern the behavioral responses of the animals to vessel presence alone versus active sonar. A single control pass was conducted on killer whales, which was insufficient to rule out vessel presence as a factor in behavioral response. During four control passes on pilot whales, Miller et al. (2011) described similar responses for two of the groups to those observed when the vessels approached with active sonar. In some cases, it is difficult to ascertain if the received SPL alone caused the reactions, or whether the repeated passes of the research vessel contributed to the observed behavioral reactions.

These data were included in the derivation of the behavioral criteria.

3.1.5.1.5 3S2 study

A follow-on Norwegian 3S study (3S2) studied behavioral reactions to sonar sources from humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), and bottlenose whales *(Hyperoodon ampullatus*). Similar methods were used as in the first 3S study, including the use of the Norwegian Navy sound source, additional smaller vessels for tagging and behavioral observations, a post-tagging baseline observation period, and the approach of the focal animal by the source vessel during the exposure periods. One difference was that while the initial course of the source vessel was set to approach the animals during the exposures, the vessel would only make small course corrections during the approach and would not change heading to continue vectoring directly at the animals.

During the minke and bottlenose whale exposures, of which there was only one each, the source vessel approached from a distance of 8 and 5 km respectively. However, during the bottlenose whale exposure the source vessel drove in a 2x2 km box around the last known position of the whale, rather than making a continuous approach, in order to acoustically track the whale as it could not be visually tracked during its long duration foraging dives. Both the minke whale and bottlenose whale showed very strong, prolonged responses to the sonar exposures, including avoidance and cessation of feeding that lasted well beyond the period of exposure. These responses began at 138 and 122 dB re 1 μPa, respectively. Since both of these whales only had a single exposure pass, it is unknown what additional contextual cues may have caused them to respond at lower received levels. However, in the case of the bottlenose whale, the number of other bottlenose whales foraging in the area during and after the exposure also decreased, indicating that these whales may be highly sensitive to noise in this region (Miller et al., 2015; Sivle et al., 2015).

One confounding factor in assessing behavioral responses found in some studies was the use of the ramp-up protocol; therefore, in this 3S2 study they approached humpback whales both with and without the use of ramp-up, to determine if the response differed. During the humpback whale exposures, the source vessel began its approach from a closer distance of approximately 1.3 km. In this case, the source vessel tried to approach each humpback whale five times: first, using a 5-min ramp up protocol; second, as a controlled silent pass with no sonar; third, using sonar but with no ramp-up; fourth, playing back killer whale vocalizations; and fifth, playing broadband noise.

The responses of the humpback whales were far more varied, and were similar to the responses by the blue whales in the SOCAL BRS (discussed below) in that they often didn't respond to exposures that reached SPLs of up to 182 dB re 1 μPa, but those that did respond often responded at lower received levels by avoiding the sound source, changing their dive profile, and ceasing to forage. There was no apparent difference in response during the ramp-up vs. no-ramp-up trials. Of the four animals with significant behavioral responses, two animals responded to the ramp-up trials (at 125 and 132 dB re 1 μPa) but not to the no-ramp-up trials, and one animal responded to both trials (at 127 and 165 dB re 1 μPa, respectively).

These data were included in the derivation of the behavioral criteria.

3.1.5.1.6 **AUTEC BRS**

Tyack et al. (2011) used the suite of 82 seafloor-mounted hydrophones at the Atlantic Undersea Test and Evaluation Center in the Bahamas to acoustically detect Blainville's beaked whales' (*Mesoplodon* *densirostris*) foraging dives before, during and after Navy mid-frequency active sonar activities. The authors found a significant reduction in foraging dives during periods of sonar operation, and found that whales that continued to dive concurrently with sonar were 2.2 – 28.9 km away from the source, with SPLs of 101 to 157 dB re 1 µPa. Moretti et al. (2014) also used the seafloor-mounted hydrophones to estimate foraging dives before, during, and after Navy sonar exercises. They developed a generalized additive model of the probability of a beaked whale dive occurring anywhere on the range, and then determined the probability of a dive occurring in the presence of sonar. The enumeration of foraging dives that occur in the presence or absence of sonar only captures a single type of response – a decrease in dives when sonar is present – and does not provide any additional information about how animals may otherwise be responding, or if they leave the range or stay on range without vocalizing.

To determine whether animals remain on the range or leave the area during sonar activities, an individual beaked whale was also tagged with a satellite tracking tag prior to an exercise (Tyack et al., 2011). During sonar, the animal moved ~17 km further from the center of the range than it was before the sonar period, and received a maximum SPL of 146 dB re 1 µPa. The animal returned to the range within 2 to 3 days after the cessation of sonar operations. This indicates movement off the range during sonar activity, but not a long-term abandonment of the area.

Two other beaked whales were tagged with DTAGs and exposed to playbacks of mid-frequency active sonar, pseudorandom noise (PRN), and killer whale calls (Tyack et al., 2011). A simulated sonar signal of ~3.5 kHz was used that had similar frequency characteristics to U.S. Navy tactical sonar (see

Table 3-1), but at lower source levels (up to 212 dB re 1 µPa @ 1 m). A PRN sound was also used to determine whether animals would respond to any sound in the mid-frequency band or if they were specifically responding to a sonar-type signal. These sources were deployed from a stationary vessel positioned about 1 km from where a beaked whale had begun a foraging dive. The signals were ramped up, from source levels of 152-160 dB re 1 µPa and increasing 3 dB every 25 seconds. The first exposed whale was exposed to MFAS in the middle of a foraging dive; it stopped clicking at an SPL of 138 dB re 1 µPa, and began a slow ascent while moving away from the sound source. A second beaked whale was tagged and exposed to pseudo-random noise during a foraging dive. This animal stopped clicking just after the last ping, with an SPL of 142 dB re 1 µPa, and also made a slow ascent to 600 m where it appeared to stop. Beaked whales have shown an increased sensitivity to sound exposure when compared to most other marine mammals, however, other factors such as prior tagging, repeated exposures, and proximity of the sound source vessel to the animal could play a strong role in mediating the observed behavioral responses.

These data were included in the derivation of the behavioral criteria.

3.1.5.1.7 SOCAL BRS

A behavioral response study conducted on and around the Navy range in SOCAL (SOCAL BRS) observed reactions to sonar and similar sound sources on a number of species: Cuvier's beaked whales (*Ziphius cavisrostrus*), a Baird's beaked whale (*Berardius bairdii*), blue whales, fin whales, and Risso's dolphins (*Grampus griseus*) (DeRuiter et al., 2013; Goldbogen et al., 2013; Southall et al., 2011; Southall et al., 2012; Southall et al., 2013; Southall et al., 2014). During most of the SOCAL BRS experiments, both simulated mid-frequency sonar and PRN were used, with the same frequency bands and source levels as in AUTEC (see

Table 3-1). The source was deployed from either a 22-m recreational dive vessel or a 35-m research vessel: this vessel was accompanied by two smaller rigid hulled inflatable boats that operated independently of the source vessel. In 2013, a few animals were also exposed using actual mid-frequency active sonar (MFAS) from U.S. Navy vessels. Tagging efforts were conducted from the rigid hulled inflatable boats, as well as photo-identification and tracking of the whales before, during, and after the exposures. One or two animals were tagged with data-recording tags, and then an observation period from 45 minutes (for mysticetes) up to 2 hours (for odontocetes) was conducted to obtain baseline behavioral data. The source vessel then positioned itself about 1 km from the tagged focal animal and deployed the sound source. Similarly to the 3S studies, the SOCAL BRS implemented a ramp-up protocol in which they started the exposure with a source level of 160 dB re 1 µPa @ 1 m and increased rapidly over a 5-10 minute period, up to 210 dB re 1 µPa @ 1 m for the simulated sonar signal and 206 dB re 1µPa @ 1 m for the PRN. However, unlike the 3S study, the source vessel did not approach the focal animal; once it was positioned, small adjustments were made to keep the sound source vertical in the water column, but otherwise it remained stationary.

Behavioral responses during the SOCAL BRS varied widely both within and across species. Many of the blue whales did not respond, even at received SPLs up to 165 dB re 1 µPa. However, those that did respond often responded at lower received SPLs (mean = 123 dB re 1 µPa). There seemed to be some behavioral context associated with whether or not animals responded; for example, deep feeding blue whales were more likely to respond than shallow feeding or traveling animals (Goldbogen et al., 2013). All beaked whales exposed to the simulated sonar responded by avoiding the source, ceasing their foraging dives, and otherwise changing their dive behavior (DeRuiter et al., 2013; Stimpert et al., 2014). However, none of the beaked whales exposed to real Navy sonar at greater distances (whether intentionally or incidentally) responded, even when the received levels were similar to the levels from the simulated sonar. In preliminary analyses, none of the Risso's dolphins or fin whales exposed to simulated or real mid-frequency sonar demonstrated any overt or obvious responses (Southall et al., 2012; Southall et al., 2013). In general, although the responses to the simulated sonar were varied across individuals and species, none of the animals exposed to real Navy sonar responded; these exposures occurred at distances beyond 10 km, and were up to 60 – 100+ km away (DeRuiter et al., 2013; B. Southall pers. comm.).

These data were included in the derivation of the behavioral criteria.

3.1.5.2 Captive Animal Behavioral Studies

Captive animal studies examine behavioral responses under controlled conditions. These studies give researchers the ability to vary the factor of interest while holding other factors stable. The received level of sound is the primary factor of interest in most of the experiments conducted to date. Within captive animal studies, the probability of behavioral response seems to be well correlated with received level indicating a primarily level-based response.

Table 3-2 describes the experimental conditions for each study in which data were used for the derivation of the Navy's Phase III behavioral response criteria.

Table 3-2: Description of experimental conditions used in captive animal behavioral studies.

Study	*Signal*	*Signal Frequency*	*Signal Duration*	*Signal Interval*	*Source Level (dB re 1 µPa @ 1m)*	*Exposure Session Duration*
Bottlenose dolphin CES[1]	Simulated Sonar	3.25- 3.45 kHz sweep/tone	1 sec	30 sec	~132-202	5 min
California Sea Lion CES[2]	Simulated Sonar	3.25- 3.45 kHz sweep/tone	1 sec	30 sec	~142-202	5 min
Hooded seal CES[3]	Simulated Sonar	1.3-1.7 kHz upsweep	1 sec	10 sec	134-194	6 min
Hooded seal CES[3]	Simulated Sonar	3.7-4.3 kHz upsweep	1 sec	10 sec	134-194	6 min
Hooded seal CES[3]	Simulated Sonar	6-7 kHz upsweep	1 sec	10 sec	134-194	6 min
Gray seal CES[4]	Tone	1 kHz	200 ms	1 min	170; 140-180	10 min
Striped dolphin CES[5]	Alarm tone	9 – 15 kHz	0.3 sec	4 sec	133 - 163	15 min
Harbor Seal CES[6]	High frequency sonar	25 kHz	50 – 900 ms	2 – 10 sec	125 – 158	30 min

[1](Houser et al., 2013b); [2](Houser et al., 2013a); [3](Kvadsheim et al., 2010a); [4](Götz & Janik, 2011); [5](Kastelein et al., 2006b); [6](Kastelein et al., 2015c)

3.1.5.2.1 Behavioral Observations during TTS Experiments

Researchers at the Navy's Marine Mammal Program (MMP) facility in San Diego, California conducted a number of controlled experiments to study noise-induced TTS in bottlenose dolphins (*Tursiops truncatus*) and beluga whales (*Delphinapterus leucas*) (Finneran et al., 2001; Finneran et al., 2003a; Finneran & Schlundt, 2004; Finneran et al., 2005b; Schlundt et al., 2000). Ancillary to the TTS studies, scientists evaluated whether the marine mammals performed their trained tasks when prompted, during and after exposure to mid-frequency tones. Altered behavior during experimental trials usually involved refusal of animals to return to the site of the noise exposure. This refusal included what appeared to be deliberate attempts to avoid a sound exposure or to avoid the location of the exposure site during subsequent tests (Finneran et al., 2002; Schlundt et al., 2000). Bottlenose dolphins exposed to 1-second intense tones exhibited short-term changes in behavior above received SPLs of 178 to 193 dB re 1 µPa, and belugas did so at received SPLs of 180 to 196 dB re 1 µPa and above. In some instances, animals exhibited aggressive behavior toward the test apparatus (Ridgway et al., 1997; Schlundt et al., 2000).

Although these data were used to derive the Phase I/II BRFs, they were not used in the quantitative derivation of the new behavioral criteria since this study was a hearing study where animals were conditioned and reinforced to tolerate high noise levels. Additionally, the controlled exposure study discussed below observed reactions of 30 bottlenose dolphins to simulated mid-frequency sonar signals and is therefore a more appropriate data set from which to derive behavioral criteria.

3.1.5.2.2 Dolphin and Sea Lion Controlled Exposure Studies

Controlled-exposure studies (CESs) have been conducted with U.S. Navy bottlenose dolphins and California sea lions (*Zalophus californianus*) at the Navy MMP facility specifically to study behavioral reactions (Houser et al. 2013a; Houser et al. 2013b). These studies were designed to expose animals at a wide variety of received levels with the specific intent of building behavioral dose-response functions with the data. Researchers noted that the sea lions and dolphins used in both studies had probably not been exposed to intense sounds such as nearby tactical sonar in the past; however, due to their training and food reinforcement, Navy animals are potentially less sensitive to noise exposure than wild animals. In both studies, animals were trained to swim across a pen, touch a target paddle, and return to the starting location. During transit, a simulated mid-frequency sonar signal was played at an SPL previously assigned to each animal. Dolphins received six different exposure levels ranging from 115-185 dB re 1 μPa (rms) and sea lions received five different exposure levels ranging from 125-185 dB re 1 μPa (rms). The transducer was located 1 m behind the target paddle so that the subject animal would have to close their distance to within 1 m of the transducer that emitted the simulated sonar signal a few seconds before. Video and audio were recorded of the session and observers that subsequently scored the sessions for behavioral responses were made blind to the exposure conditions.

Behavioral reactions included increased respiration rates, fluke or pectoral fin slapping (dolphins), prolonged submergence (sea lions), and refusal to participate, among others. Twenty dolphins that received exposures of 115 – 160 dB re 1 μPa (rms) had significant behavioral reactions on only 5 out of 200 trials. It was determined that bottlenose dolphins were more likely to respond to the initial trials, but habituated to the sound over the course of 10 trials except at the highest received levels (175 and 185 dB re 1 μPa [rms]). One out of three California sea lions exposed to the 125 dB re 1 μPa (rms) treatment and one out of three exposed to the 155 dB re 1 μPa (rms) treatment showed significant reactions on all ten exposure trials, while the other four individuals at the same levels did not show a significant response on any trial. Sea lions showed consistent significant responses on almost all trials at the 170 and 185 dB re 1 μPa (rms) levels. Unlike dolphins, sea lions did not habituate over the course of ten exposure trials and younger animals were more likely to respond than older animals. This indicates that age or life experience may play a large role in mediating responses to noise exposure in sea lions. In both the sea lion and dolphin controlled exposure studies, the probability of behavioral reactions was well correlated with received level indicating a primarily level-based response.

These data were included in the derivation of the behavioral criteria. They are also used indicate the sound levels at which level-based responses are more likely to occur.

3.1.5.2.3 Hooded Seal Controlled Exposure Study

Captive hooded seals (*Cystophora cristata*) were exposed to tonal signals in the 1 to 7 kHz band to determine the received SPL at which these animals would respond (Götz & Janik, 2010; Kvadsheim et al., 2010b). Hooded seals were exposed to three different mid-frequency upsweeps (1.2 – 1.7 kHz, 3.7 – 4.3 kHz, and 6 – 7 kHz) that started at a source level of 134 dB re 1 μPa @ 1 m and increased to 194 dB re 1 μPa @ 1 m; received levels were 10 – 27 dB lower depending on the animal's position in the netted enclosure. The animals' dive frequency and time spent at surface were monitored during the exposures, and changes to these were used as metrics of response. The seals showed no responses to received SPLs below about 160 dB re 1 μPa; once SPLs were between 160 – 170 dB re 1 μPa, the seals began actively avoiding the sound source (at 5 m depth) by reducing their dive activity, rapidly swimming at the surface, and floating with their heads out of the water (Kvadsheim et al., 2010b).

These data were included were included in the quantitative derivation of the behavioral criteria.

3.1.5.2.4 Gray Seal Controlled Exposure Studies

Gotz and Janik (2011) exposed wild-caught gray seals (*Halichoerus grypus*) to a 1 kHz “startle” sound to investigate the signal characteristics associated with the triggering of the startle response. Animals were kept for a short time at the Sea Mammal Research Unit (SMRU) of St. Andrews, Scotland before being released. The seals were first exposed to received SPLs of 170 dB re 1 µPa, then to increasing SPLs from 140 to 180 dB re 1 µPa in 5 dB increments. Five out of the seven exposed animals responded initially at 170 dB re 1 µPa, then with a mean of 159 dB re 1 µPa, while two did not respond at all. During the course of the study, the animals that responded began sensitizing to the sound and their responses included cessation of feeding and avoidance of the sound source.

Götz (2008) also conducted boat-based playbacks of a variety of signals, including the startle stimuli used for the captive study. While he did observe that the number of animals close to the boat (e.g., within ~ 80 m) decreased and the number of animals further from the boat (~80-100 m) increased from the pre-exposure period to the during-exposure period, there was no way of knowing if the same animals were observed during each period.

Due to the types of responses obtained, some of the results of Gotz and Janik (2011) were included in the quantitative derivation of the behavioral criteria. While the results from Götz (2008) likely demonstrate avoidance of the sound source, the data could not be used for the quantitative derivation of the behavioral criteria because observed responses of individuals could not be correlated with specific received levels.

3.1.5.2.5 Striped Dolphin and Harbor Porpoise Alarm Study

Kastelein et al. (2006a) exposed a striped dolphin (*Stenella coeruleoalba*) and a harbor porpoise to an experimental acoustic alarm with a set of 16 tones with fundamental frequencies between 9 and 15 kHz. SPLs in the pen ranging from 116 dB re 1 µPa (for the fundamental 11 kHz tone) to 138 dB re 1 µPa (for the third harmonic of the 11 kHz tone). While the harbor porpoise responded by increasing its distance from the source (e.g., remaining on the opposite side of the pen) and increasing its respiration rate, the striped dolphin did not significantly change its distance to the source or respiration rate.

Since there is no data available that pairs the animals’ received level with behavioral response, these data were not used in the quantitative derivation of the behavioral criteria.

3.1.5.2.6 Harbor Seal High Frequency Sonar Study

Kastelein et al. (2015c) exposed two harbor seals (*Phoca vitulina*) to three different sonar signals around 25 kHz, with three averaged received levels across the pool (125 – 135, 137 – 147, and 156-158 dB re 1 µPa, depending on the sonar type). For two of the three signals, behavior did not change even at the highest average received levels. For the third, frequency modulated sonar signal, the seals swam faster, swam with their heads out of the water 2-4% more, and hauled out 1-2% more frequently at the intermediate and highest average received levels than during baseline periods. However, these responses were not tested statistically for significance, and at such low increments of increase were deemed not to rise to the level of a significant behavioral response under military readiness and were therefore not used in the derivation of the behavioral criteria.

3.1.6 Marine Mammal Species Groups

Data on behavioral responses to sonar and other transducers exist for relatively few species, which necessitates that species be divided into groups of related animals, either phylogenetically or by known species sensitivities and responses. The six primary groups for application of the Phase III criteria are Odontocetes (not including beaked whales or harbor porpoise), Pinnipeds, Mysticetes, Beaked Whales, and Harbor Porpoises. Little to no behavioral response data exists for manatees; as such, they are assigned to a surrogate behavioral criteria group.

The Odontocete group includes all oceanic toothed whales, with the exclusion of beaked whales and harbor porpoises. Behaviorally, odontocetes tend to have strong and complex social bonds, forming groups that range from a few to thousands of animals (Reeves et al., 2002). In many odontocete species these groups are comprised of related animals, and these join with other groups for mating and breeding. In other odontocetes, particularly the smaller delphinids, their social structure is more fission-fusion, with groups forming and reforming on timelines ranging from hours to days. This gregariousness often leads dolphins and porpoises to approach and swim within the pressure wave generated by moving ships and boats, a behavior known as bow riding. Not all species join in this behavior, and some appear to actively avoid vessels rather than approach (Henderson et al., 2014). All odontocetes use echolocation to navigate and hunt for prey, and in some cases for communication as well. Many odontocetes also vocalize using whistles and burst pulses, and these can range from simple flat whistles to complex, multi-part vocalizations that may be pod- or even individually-specific (Ford & Fisher, 1982; Lammers et al., 2003; Richardson et al., 1995). Due to similarities in behavioral traits and close taxonomic links, odontocetes (excluding beaked whales and harbor porpoises) are assigned to a single behavioral criteria group.

The Pinniped group is comprised of all phocids, otariids, and odobenids. Animals within this group spend their time both on land and at sea, although in varying degrees for different species (Reeves et al., 2002). While some species are found in remote locations, the dependence on land causes many pinniped species to be in close association with humans. Pinnipeds produce vocalizations in air and under water; these include calls between mothers and pups, alarm calls, mating displays, and aggressive exchanges between males, among others (Schusterman et al., 2001). Due to similarities in behavioral traits and close taxonomic links, pinnipeds are assigned to a single behavioral criteria group.

The Mysticete group contains all the baleen whales. Mysticetes are unique among marine mammals in that they have developed the use of baleen plates to filter fish, krill, zooplankton, and amphipods out of the water, although each family of mysticete has developed a different foraging specialization (Reeves et al., 2002). Baleen whales are the largest mammals, ranging from 20 to over 100 feet in length, and they produce low- and mid-frequency vocalizations, from 20 Hz up to 20-30 kHz (Richardson et al., 1995). These calls range from simple sweeps and moans to complex songs, and due to their lower frequency and high amplitude (120-190 dB re 1 µPa @ 1 m) they can be detected for hundreds of kilometers in the ocean. There is some evidence that baleen whale calls are increasing in amplitude (Parks et al., 2007a; Parks et al., 2011) or changing frequency (McDonald et al., 2009) in order to compete with the increasing background noise in the world's oceans. Due to similarities in behavioral traits and close taxonomic links, mysticetes are assigned to a single behavioral criteria group.

Beaked Whales (family Ziphiidae) are a generally cryptic group, difficult to observe at the surface and tending to avoid vessels and underwater noise (Barlow & Gisiner, 2006). Beaked whales are deep divers, diving to depths of over 1-2 km to forage on squid and mesopelagic fish (Reeves et al., 2002; Schorr et al., 2014). Due to several mass stranding events of beaked whales in proximity to Navy training events (D'Amico et al., 2009), this group has been deemed highly sensitive to sonar and other active acoustics and they are considered separately from the other odontocetes.

Similarly, Harbor Porpoise have been shown to be highly sensitive to underwater noise, including acoustic pingers (Kastelein et al., 2000; Teilmann et al., 2006), pile driving (Kastelein et al., 2013d; Tougaard et al., 2009), and impulsive sounds (Kastelein et al., 2013c). The harbor porpoise is one of the smallest marine mammal species, and has a history of being hunted or incidentally caught by fisheries (Reeves et al., 2002). They are coastally distributed, further bringing them into contact with human activity. Due to these noted sensitivities, harbor porpoises are considered separately from the other odontocetes.

Manatees are another coastally distributed species that have a history of negative interaction with people; however, unlike harbor porpoise they may not be sensitive to noise. Rather, due to their slow swimming speeds and low profile at the surface, their main issue has been with vessel strikes, particularly by small watercraft (Jett et al., 2013; Nowacek et al., 2004b). Vessel noise may also be a concern (Miksis-Olds et al., 2007), but there is little other information available about manatee responses to other noise sources, including active sonar. Mysticetes, although distant, are the most closely related group of marine mammals taxonomically and share important behavioral traits (e.g., grazing); therefore, manatees are assigned to the mysticetes behavioral criteria group.

No data can be found on polar bear or sea otter reactions to underwater sounds, especially those from sonar or other transducers. Polar bears spend a good deal of their time on land or ice and little time with their heads submerged below the surface when they are swimming or hunting. Sea otters live in shallow coastal areas and spend a great deal of time floating at the surface, or conducting short foraging dives. Navy at-sea training and testing activities have little to no overlap with the range of these species, and therefore will not be analyzed further.

3.1.7 Dose and Contextual responses

The received level of sound may not always be the best predictor of a marine mammal's behavioral reaction to a sound exposure. The context, including the animal's behavioral state, animal's previous experience with the sound, sound source speed and heading (either toward or away), and sound source distance, can all affect an animal's reaction (Southall et al., 2007; Wartzok et al., 2003). Ellison et al. (2011) proposed dividing behavioral reactions into *level-based responses* and *context-based responses* (see Figure 3-2). At higher amplitudes, a *level-based response* relates the received sound level to the probability of a behavioral response which is probably caused by auditory masking or annoyance (Ellison et al., 2011). At lower amplitudes, sound can cue the presence, proximity and approach of a sound source and stimulate a *context-based response* based on factors other than received sound level (e.g., the animal's previous experience, sound source-animal separation distance, behavioral state [e.g., feeding, traveling]). It is highly probable based on evolutionary pressures for sound source localization in marine mammals (e.g., for mate localization, predator avoidance) that animals can distinguish the proximity of a sound source based on other characteristics of the received signal besides amplitude (e.g., multipath characteristics, frequency content, signal distortion).

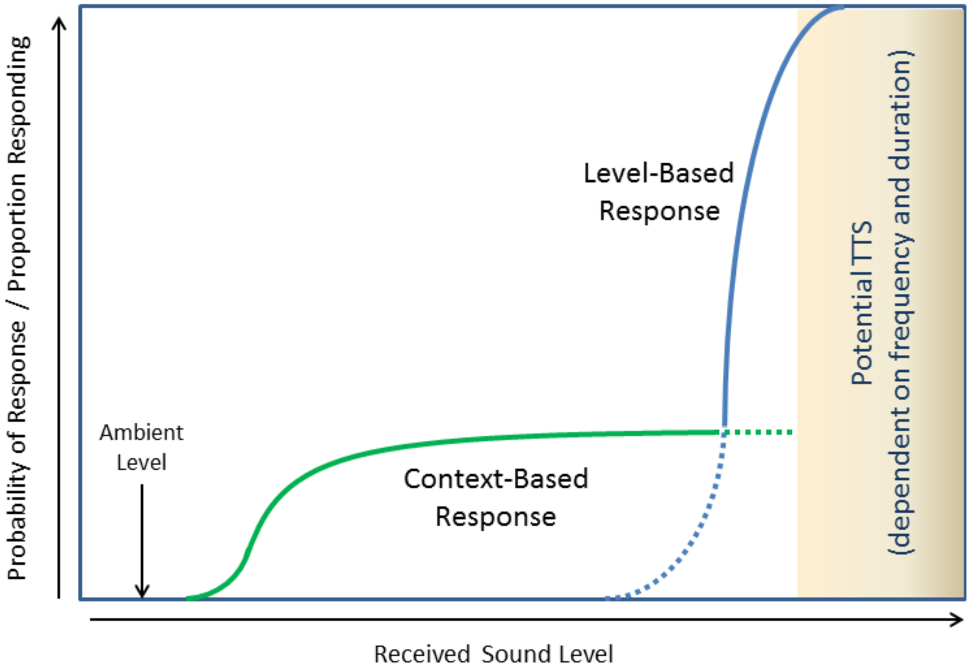

Figure 3-2. Conceptual framework for dividing behavioral responses due to acoustic disturbance into context- based and level-based responses (Ellison et al., 2011).

The currently available field-based behavioral response studies (discussed above) do not portray a clear relationship between the received level of sound and the probability of a behavioral reaction. For example, in the case of the blue whales studied in the SOCAL BRS, higher received levels were sometimes associated with a lower probability of reaction (pers. comm. B. Southall, December 2014). This indicates that the received sound level is not necessarily mediating the probability of a behavioral reaction *per se*, but perhaps only indicating the presence and movement of the vessel and sound source. In the case of the blue whales studied in the SOCAL BRS, behavioral reactions were more closely correlated with feeding state than received sound level.

Other studies discussed above (e.g., 3S) also share similar results: the received level of sound does not correlate well with the probability of a significant behavioral response. In these cases, a number of other factors likely contributed to the responses, such as repeated encroachment to within a few hundred meters, close proximity of multiple vessels, and cutting in front of the animals' path with the source vessel (often referred to as 'leapfrogging' the animals). These other factors have been studied in the absence of sonar with respect to vessel traffic and whale watching. Killer whales also show behavioral changes in the close proximity of multiple vessels (Williams et al., 2014) and when being encroached upon by small boats including kayaks (Williams et al., 2011). Bottlenose dolphins have been shown to reduce foraging in the presence of boats, independent of sound level (Pirotta et al., 2015) and to avoid intrusive vessels (Lusseau, 2006). Christiansen et al. (2013) showed that minke whales decrease foraging in the presence of whale watching vessels. This research provides insight into other factors that may be mediating behavioral responses at low to moderate sound levels during some field-based behavioral response studies discussed in Section 3.1.5.1.

In relation to the conceptual model shown in Figure 3-2, many of the responses from field-based behavioral studies occur at moderate to low sound levels, in several cases close to the ambient noise level (Miller et al., 2012). As mentioned previously, these reactions do not show an increased probability with increasing received sound level; therefore, it is likely that these reactions are primarily mediated by contextual factors and would fall under the "Context-Based Response" (green curve) on Figure 3-2. In contrast, results from the controlled exposure sessions using Navy dolphins and sea lions represent reactions that are primarily mediated by the sound level and therefore fall under the "Level-Based Response" (blue curve) in Figure 3-2. This is an important distinction because within the region of context-based response, factors other than sound level, such as proximity and motion of the sound source, are likely to be more important factors in predicting a significant behavioral response.

As discussed below in the Section 3.1.8, a biphasic curve provided the best fit to the existing behavioral response data when received level alone is used as the independent variable dictating the probability of a significant response. The biphasic curve is actually a series of two sigmoidal curves that approximates the shape of the illustration in Figure 3-2. As discussed above significant reactions at lower to moderate received levels are mediated by factors other than sound level; but nevertheless, data that relates received level to behavioral reaction is what is currently available. The Navy will take into consideration other factors besides received level when available at low to moderate sound levels when estimating significant behavioral responses to sonar and other transducers during training and testing activities.

3.1.8 Behavioral Response Functions and Thresholds for Sonar and Other Transducers

Behavioral response studies that were designed to record behavioral observations and contained detailed data on reactions at specific received sound levels were used quantitatively in the derivation of the Phase III behavioral criteria. Specifically, data needed to meet both of the following criteria to be used in the quantitative derivation:

- Observations of individual/group animal behavior were related to known or estimable received levels.
- The study was primarily designed to observe behavioral changes during controlled exposures or actual Navy activities (i.e., monitoring).

Data from the applicable studies (see Table 3-3 through Table 3-7 below) were obtained from published materials. Exposure and behavioral response data for the 3S and BRS studies were also directly discussed with the researchers (P. Miller, P. Wensveen, P. Kvadsheim, F.P. Lam, B. Southall, J. Goldbogen, and J. Calambokidis). In addition, D. Houser (Dolphin and Sea Lion CES) is a contributor to this report. Finally, L. Thomas and P. Wensveen contributed significantly to the Bayesian methodology from which the Navy derived response functions.

Limited data exist for behavioral responses of harbor porpoises, sirenians, and sea turtles to sonar and other transducers. For harbor porpoises, the information currently available suggests a very low threshold level of response for both captive and wild animals, and the mysticete BRF will be used as a proxy for sirenians. Existing behavioral data to air gun exposures (See McCauley et al., 2000) was applied for sea turtles.

3.1.8.1 Bayesian Biphasic Model

A Bayesian biphasic dose response function was developed that was a generalization of the monophasic function previously developed and applied to BRS data (Antunes et al., 2014; Miller et al., 2014). As discussed in Section 3.1.5, individual animals in these data may have undergone multiple controlled exposure sessions (one or more consecutive, replicate trials); for each session the animal had some threshold, t, at which it did or did not respond. There were generally two types of data used for this analysis. The first was received levels taken from tagged animals during behavioral response studies on wild animals exposed to an escalating level of sonar (Section 3.1.5.1). In that case either the received level at the time of the first significant response (as described in Section 3.1.2) or the maximum received level of that exposure if no response occurred was used. Multiple exposures could have occurred per animal, but only one received level per session was used in the model. The second type of data was from controlled exposure studies on captive animals (Section 3.1.5.2). In some of these, an animal was only exposed to a single received level, which was the level input into the model, whereas in others an animal may have been exposed to an escalating received level, for which the level at the time of the response or the maximum level exposed was used in the model.

In the monophasic approach previously used (Miller et al., 2014), this threshold was sampled from a truncated normal distribution; this normal distribution had an overall mean, a between-whale standard deviation and a between-trial within-whale standard deviation. Because each threshold was sampled from a truncated normal distribution, the overall dose response function can be thought of (approximately) as coming from a cumulative truncated normal distribution function (CDF), giving the characteristic "S"-shape. It is approximate because each trial has its own CDF and the overall function is a mixture of these CDFs.

Here, we generalized by allowing the threshold to come from one of two truncated normal distributions, one with lower exposure values than the other. Following the logic of Ellison et al. (2011), the lower distribution is referred to as context-dependent, while the upper is dose-dependent (although note that both distributions are, in fact, dose-dependent). The upper function could also be thought to be driven by uncomfortable loudness, or perhaps, annoyance (Ellison et al., 2011). One may expect the standard deviation of the context-dependent function to be larger than the dose-response function, leading to a "flatter" CDF, and also to have the probability for each animal and trial of the threshold being sampled from the lower function being dependent on context-related covariates (so "context-dependent") (Figure 3-2Figure 3-2).

The generalized marine mammal Bayesian biphasic dose response function is made up of two truncated cumulative normal distribution functions (CDF) with separate mean (nu_1 and nu_2) and standard deviation (tau_1 and tau_2) values, as well as upper (U) and lower (L) bounds. The upper bound of the lower CDF, or the context-dependent response portion, has the same value as the lower bound of the upper CDF, or the dose-response response portion (e.g., $U_1 = L_2$). This value is another parameter determined by the model, with the bounds falling between 120 and 160 dB. The model assumes all animals have the same mean and standard deviation parameters (and hence the same context-dependent response function and dose-dependent response functions), but that they differ in how likely they are to display the context-dependent function as opposed to the dose-dependent function in a given exposure session. The probability of whale *i* displaying the context-dependent response in a particular exposure session is given in the model by the value of pi_i – for example, if $pi_i = 0.7$ then there is a 70% chance that the context-dependent function will be used in determining whether there is a response and a 30% chance that the dose-dependent function will be used. The value for pi for each whale is determined by two parameters – a mean, mu, and a standard deviation, phi. As is common when modelling probabilities (in this case, the probability of having a context-dependent as opposed to dose-dependent function), pi is modeled on the probit scale – in other words pi comes from a normal CDF with mean (mu) and standard deviation (phi). Mu should, realistically, stay in the range -2 to 2 if the biphasic pattern is present in the data: when mu is -2, the expected value of pi is 0.02 – i.e., we expect only 2% of animals to display context-dependent response functions; when mu is 2 the expected value of pi is 0.98, i.e., we expect 98% of animals to have context-dependent responses. Similarly, phi (which indexes the between-whale variability in pi) is unlikely to be more than 2.

After discussion with subject matter experts, the following priors were used on model parameters for all taxa. The curve was fit between 90 and 185 dB, with the bound between the curves falling between 120 and 160 dB (as discussed above). The variance, or tau, was chosen to be narrow in order to have the biphasic equation fit the underlying data.

- $U_1=L_2$~uniform(120,160)
- nu_1~uniform(90,U_1); tau_1~uniform(0,10)
- nu_2~uniform(L_2,185); tau_2~uniform(0,10)
- mu~normal(0,10); phi~uniform(0,10)

The controlled exposure experiment data could have been left or right censored. Left censoring occurred when the animal responded at the lowest exposure level, or when the experimental protocol did not involve dose escalation but instead application of a single exposure level per experimental trial. In the latter case, if the animal responded at the given dose, the data were always left-censored because we do not know if the animal would have responded at a lower dose. Right censoring occurred when the animal did not respond to any exposures in an experimental trial; in that case, we only know that the response threshold for that animal was somewhere between the maximum exposure level of that trial and some high value where all animals are assumed always to respond (in this case, we used 185 dB).

As with the monophasic models, a measurement precision was implemented to account for uncertainty in received level measurements because of variations in the sound field of test pools, and, for field studies, variation in tag hydrophone sensitivity and potential influences of body shielding. In this case we used a standard deviation of 2.5 dB, the same as was used in (Antunes et al., 2014; Miller et al., 2014) but the exact value was found to have little influence on the model outcomes.

The model was fitted to data using the Markov Chain Monte Carlo (MCMC) algorithm, implemented in the software JAGS (Plummer, 2012). Convergence diagnostics and other post-processing was implemented in the software R (R Core Team, 2016). Convergence was assessed by examining trace plots and the BGR statistic (Brooks & Gelman, 1998) for each parameter, using three MCMC chains run from random start points for 20,000 iterations. We determined convergence was achieve after <10,000 iterations in all cases, and so inference was based on a burn-in of 10,000 iterations followed by 50,000 samples thinned by a factor of 10. The resulting Monte Carlo error in estimates was negligible.

3.1.8.2 Biphasic Equation Fit

In order to generate equations that could be used in the Navy Acoustic Effects Model (NAEMO), the Navy fit a standard Biphasic dose response function to the posterior median dose response values generated using the Bayesian model for each taxonomic group. Fitting was done using Graphpad Prism (Graphpad, 2007) and was achieved by minimizing the sum of squared deviations between the posterior median evaluated at integer dose levels from 90 to 185 dB and the estimated value from the standard function. The standard function used was:

Eq. (1) $$P(L_R) = [\frac{p}{1+10^{(L_1-L_R)h_1}}] + [\frac{1-p}{1+10^{(L_2-L_R)h_2}}\ ]$$

where $P(L_R)$ is the probability of response, L_R is the received SPL (dB re 1 µPa), p is the proportion of the curve comprising the context-dependent portion of the curve, L_1 is the SPL at the midpoint proportion of the first phase (the context-dependent portion), L_2 is the SPL at the midpoint proportion of the second phase (the dose-response portion, and h_1 and h_2 are the hill slopes of the two phases (Graphpad, 2007).

The final values for each curve are given in (Section 3.2); the following sections contain detailed discussions of how these parameters were derived for each of the behavioral response functions.

3.1.8.3 Odontocetes

Overall exposure levels are given for each species/study group

Table 3-3). Responses occurred at received levels ranging from 94 to 185 dB re 1 µPa, the means of the response data were between 126 and 169 dB re 1 µPa (Figure 3-3). This wide variation in received levels at which responses occurred indicates the contextually-dependent nature of behavioral responses in the field studies. These data were fit using the methods described above, however for the controlled exposure study (CES) data all ten exposure sessions per individual animal were combined into one response, such that an overall response was assumed to have occurred if the animal responded in any single trial. This was done to give equal weighting to the data from the field studies and the CES. The resulting response function is shown in Figure 3-4, with a 50% probability of response at 157 dB re 1 µPa.

Table 3-3. Odontocete data relied upon for quantitative assessment of behavioral response.

Species	*Study*	*# Individuals*	*# Exposure Sessions*	*Range of Exposure Received Levels (dB re 1 µPa)*
Killer Whale	3S (Miller et al., 2011; Miller et al., 2014; Miller et al., 2012)	4	8	71 - 174
Pilot Whale	3S (Antunes et al., 2014; Miller et al., 2011; Miller et al., 2012)	5	11	70 - 180
Sperm Whale	3S (Miller et al., 2011; Miller et al., 2012)	4	10	73 - 170
Bottlenose Dolphin	CES (Houser et al., 2013a)	30	30	115 - 185

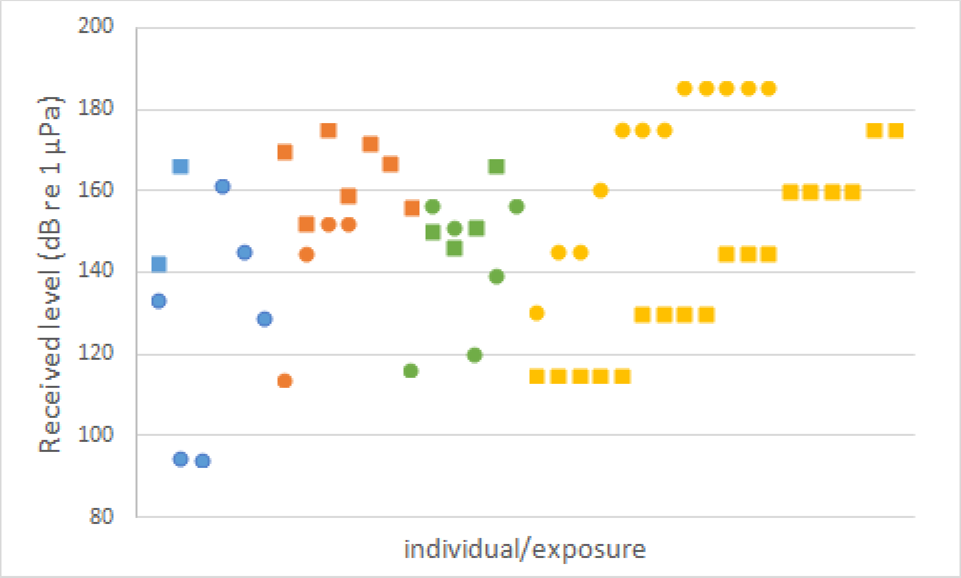

Figure 3-3. Received levels at the time of Odontocete responses (in circles) or maximum received levels when there was no response (in squares). 3S killer whales are shown in blue, 3S pilot whales are shown in orange, 3S sperm whales are shown in green, and CES bottlenose dolphins are shown in yellow.

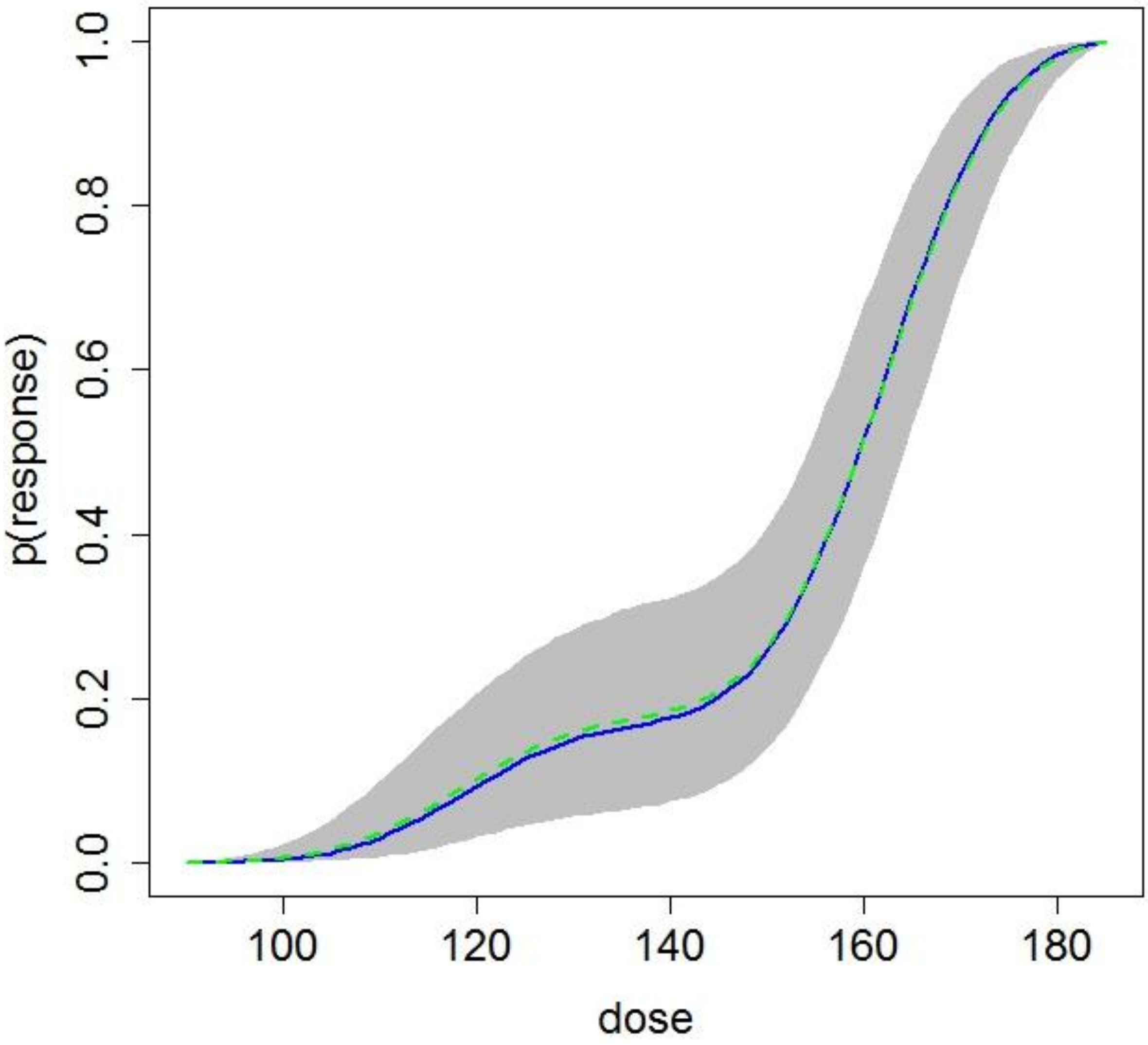

Figure 3-4. The Bayesian biphasic dose-response BRF for Odontocetes. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

3.1.8.4 Pinnipeds (In-Water)

All in-water pinniped data were derived from controlled exposure experiments on captive animals; there are no data available on responses of wild pinnipeds to sonar or other transducers.

Table 3-4: Pinniped data relied upon for quantitative assessment of behavioral response.

Species	***Study***	***# Individuals***	***# Exposure Sessions***	***Range of Exposure Received Levels (dB re 1 µPa)***
Hooded Seal	CES (Kvadsheim et al., 2010a)	4	4	110 - 170
Gray Seal	CESa (Götz & Janik, 2011)	7	7	170
Gray Seal	CESb (Götz & Janik, 2011)	7	7	140 - 180
California Sea Lion	CES (Houser et al., 2013b)	15	15	125 - 185

Overall exposure levels are given for each species/study group (Table 3-4); responses occurred at received levels ranging from 125 to 185 dB re 1 µPa (Figure 3-5). However, the means of the response data were between 159 and 170 dB re 1 µPa. Hooded seals were exposed to increasing levels of sonar until an avoidance response was observed, while the gray seals were exposed first to a single received level multiple times, then an increasing received level. Each individual California sea lion was exposed to the same received level ten times, and as above for the bottlenose dolphin CES these exposure sessions were combined into a single response value, with an overall response assumed if an animal responded in any single session. Because these data represent a dose-response type relationship between received level and a response, and because the means were all tightly clustered, the Bayesian biphasic BRF for pinnipeds most closely resembles a traditional sigmoidal dose-response function at the upper received levels (Figure 3-6**Error! Reference source not found.**), and has a 50% probability of response at 166 dB re 1 µPa.

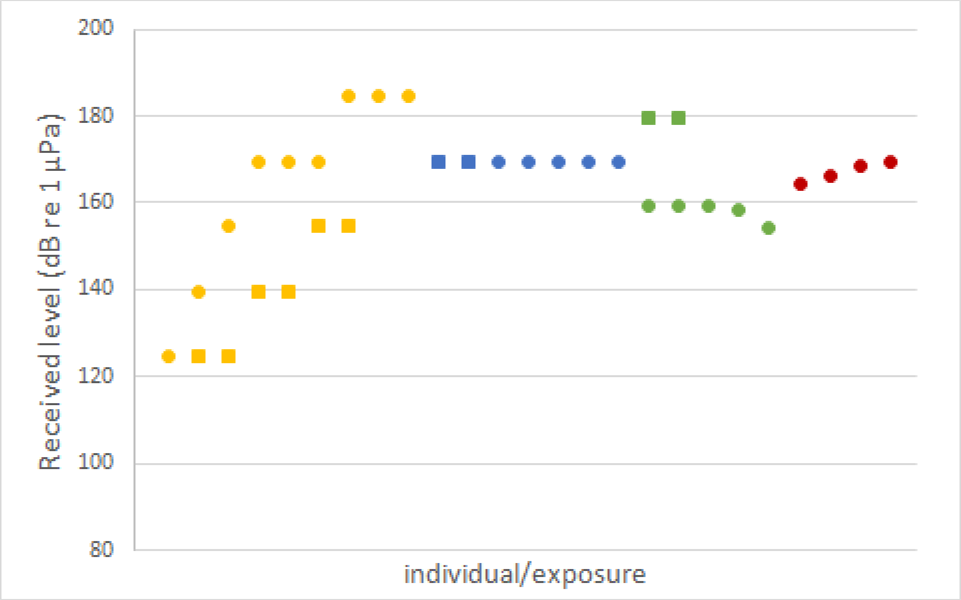

Figure 3-5. Received levels at the time of Pinniped responses (in circles) or maximum received levels when there was no response (in squares). CES California sea lions are shown in yellow, CESa gray seals are shown in blue, CESb gray seals are shown in green, and CES hooded seals are shown in red.

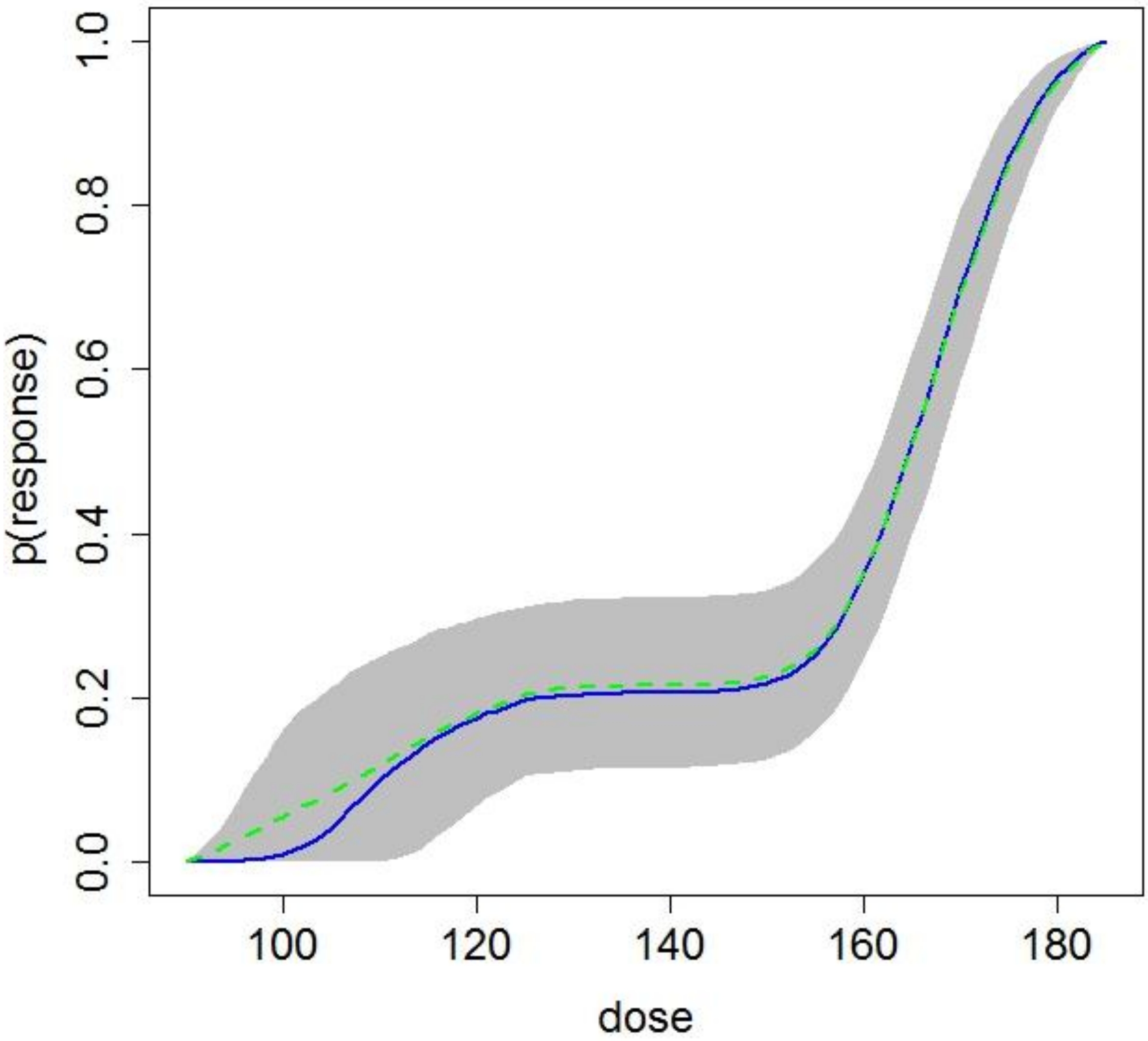

Figure 3-6. The Bayesian biphasic dose-response BRF for Pinnipeds. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

3.1.8.5 Mysticetes

During the SOCAL BRS two signal types were presented to the whales – a sonar-like signal (similar to the 3S and CES studies), and a broadband noise signal in the same bandwidth. Final response curves used all available noise sources to be more robust against all steady state noise types. Mysticetes in these behavioral response studies were observed to generally either respond at lower received levels (< 160 dB re 1 µPa) or to not respond at any received level (Figure 3-7). As mysticete exposures occurred largely at lower received levels, with a maximum exposure level at 175 dB re 1 µPa, the estimated probability of response increased steeply between this level and the level of 185 dB re 1 µPa at which all animals were assumed to respond (Figure 3-8). The resulting curve had a 50% probability of response at 177 dB re 1 µPa.

Overall exposure levels were estimated for each species/study group (Table 3-5); responses occurred at received levels ranging from 107 to 165 dB re 1 µPa (Figure 3-7), but the means of the response data were between 123 and 139 dB re 1 µPa. The high variability in responses at low received levels is indicative of the contextually-dependent nature of behavioral responses. Most mysticetes did not respond at all, and those that did were at relatively low to moderate received levels. This was likely due to the number of context-based variables inherent in these studies; there was often more than one vessel present, the vessel(s) were often very close (within 1-3 km) to the focal whales, and those whales that did respond (e.g., the blue whales from the SOCAL BRS) were typically engaged in more “sensitive” behaviors – deep foraging dives in the case of the blue whales (Goldbogen et al., 2013).

Table 3-5: Mysticete data relied upon for quantitative assessment of behavioral response.

Species	*Study*	*# Individuals*	*# Exposures*	*Range of Exposure Received Levels (dB re 1 µPa)*
Blue Whale	SOCAL BRS (Goldbogen et al., 2013; Southall pers. Comm.)	16	30	94 - 165
Humpback Whale	3S (Sivle et al., 2015)	10	20	85 - 182
Minke Whale	3S (Sivle et al., 2015)	1	1	83 - 158
North Atlantic Right Whale	Ship Alarm (Nowacek et al., 2004a)	6	6	133 - 148
Fin Whale	LFA Playbacks (Clark et al., 1999)	6	6	115 - 148
Blue Whale	LFA Playbacks (Clark et al., 1999)	1	1	95 - 150
Humpback Whale	LFA Playbacks (Clark et al., 1999)	17	17	121 - 150

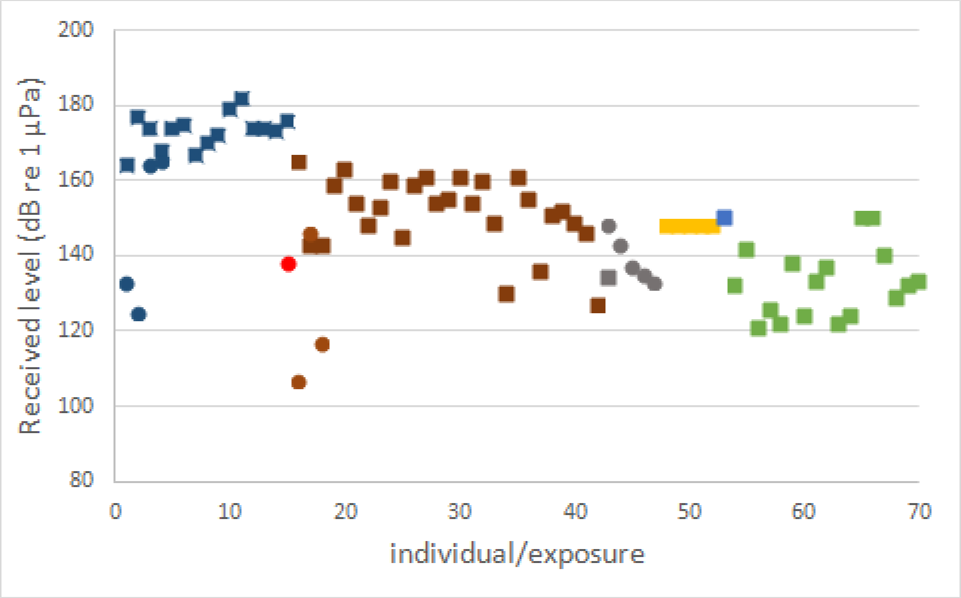

Figure 3-7. Received levels at the time of Mysticete responses (in circles) or maximum received levels when there was no response (in squares). 3S humpbacks are shown in dark blue, the 3S minke whale is shown in red, BRS blue whales are shown in brown, North Atlantic right whales are shown in gray, LFA fin whales are shown in yellow, the LFA blue whale is shown in light blue, and LFA humpback whales are shown in green.

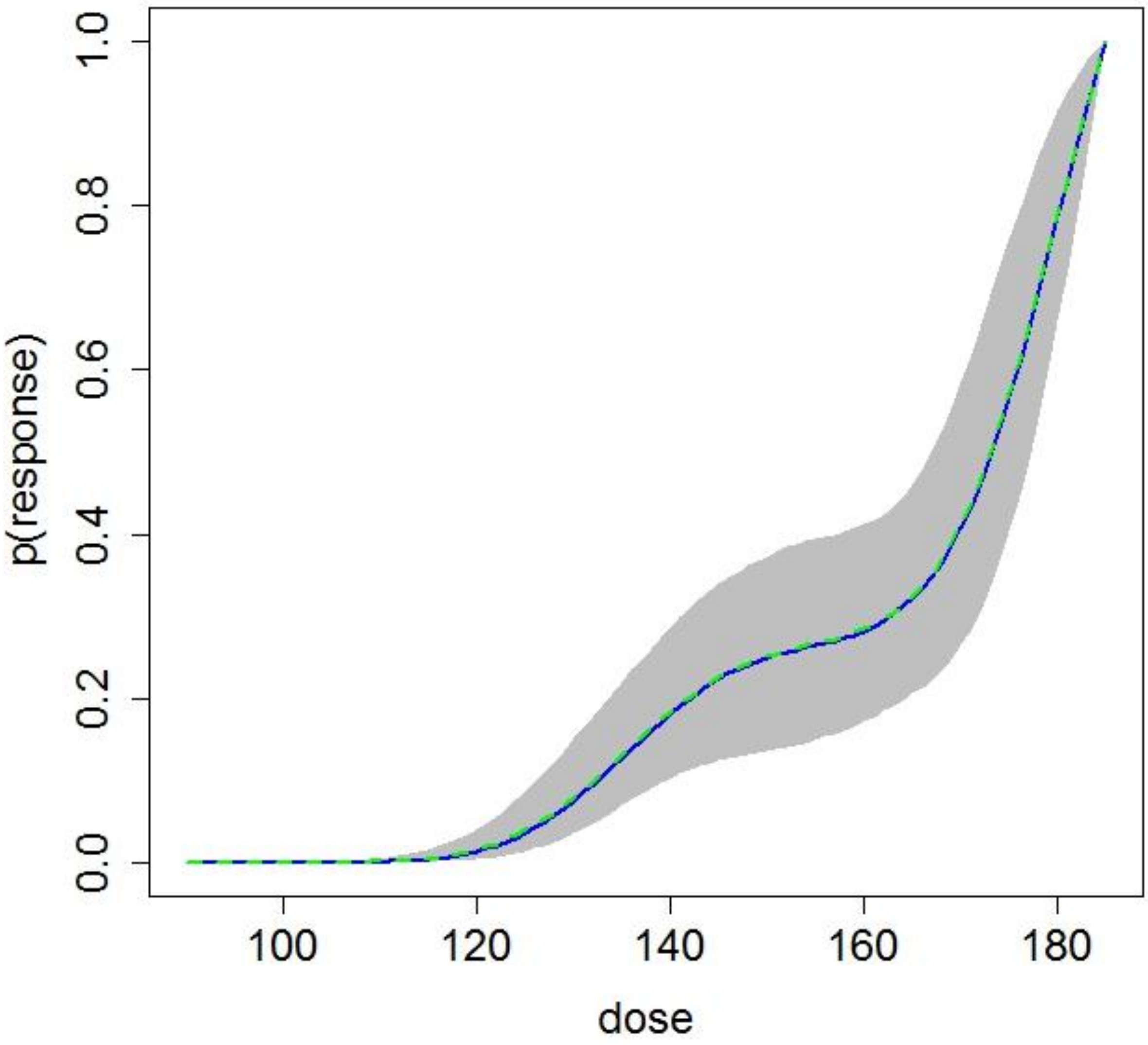

Figure 3-8. The Bayesian biphasic dose-response BRF for Mysticetes. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

3.1.8.6 Beaked Whales

The behavioral response data from the BRS and 3S studies were limited, and some responses occurred at relatively low received SPLs (Figure 3-9). However, these are again likely tied to the context of the exposures. In the 3S study the vessel was directed at the bottlenose whale and continued vectoring around the animal, while in the SOCAL BRS there were multiple vessels within 1-3 km of the animals. It should be pointed out that the third SOCAL BRS beaked whale that did not respond (

Table 3-1) was exposed to MFA sonar from an actual Navy vessel located over 65 km away from the animal. Although not included in this dataset, another beaked whale in the SOCAL BRS was incidentally exposed to real Navy sonar during a simulated sonar experiment. It did not respond to the real sonar, even though it occurred at received levels similar to those received during the simulated sonar playback when it did respond (DeRuiter et al., 2013). This may provide some evidence that the proximity of the source rather than the received level alone contributes to the response of the animal, since these exposures occurred at similar received levels but with different outcomes.

In addition to the data shown in Table 3-7, the Moretti et al. (2014) data was also used in the derivation of the beaked whale BRF. The Moretti et al. (2014) data (Table 3-6) is from actual multiplatform, multiday anti-submarine warfare (ASW) training. The data from the Generalized Additive Model (GAM) was used rather than the Generalized Linear Model (GLM) fit to be most consistent with the other data sources use herein to derive BRFs; the GAM data represents the response that was actually measured, whereas the GLM line fit was a smoothed function derived to fit between 0 and 100% probability of response. The GAM function extends from 120 to 180 dB re 1 μPa and has a 50% probability of response at a SPL of 150 dB re 1 μPa (Moretti et al., 2014).

Table 3-6: Beaked whale data relied upon for quantitative assessment of behavioral response.

Species	*Study*	*# Individuals*	*# Exposures*	*Range of Exposure Received Levels (dB re 1 μPa)*
Bottlenose Whale	3S (Sivle et al., 2015)	1	1	72 - 151
Cuvier's and Baird's Beaked Whales	BRS (DeRuiter et al., 2013; Stimpert et al., 2014; Southall pers comm. 2014)	4	5	91 - 143
Blainville's Beaked Whales	(Moretti et al., 2014)	unknown	>106	120 - 180
Blainville's Beaked Whales	(Tyack et al., 2011)	2	2	<100 - 142

Table 3-7: Individual beaked whale exposure data and associated received levels (RL) and distances.

Individual/Exposure	*Study*	*Source*	*Year*	*Species*	*RL at Resp*	*Max RL No Resp*	*Distance (km)*
#1 - ha13_176	3S2	Simulated MFA	2013	Bottlenose whale	122	NA	< 5
#2 - bb12_214a	BRS	Simulated MFA	2012	Baird's beaked whale	NA	138	3 - 5
#3 - zc11_267a	BRS	Simulated MFA	2011	Cuvier's beaked whale	95	NA	3 - 5
#4 - zc13_210a	BRS	Real MFA	2013	Cuvier's beaked whale	NA	124	> 60
#4 - zc13_210a	BRS	Incidental MFA	2013	Cuvier's beaked whale	NA	115	> 60
#5 - zc10_272a	BRS	Simulated MFA	2010	Cuvier's beaked whale	98	NA	3 - 5
#6 – no ID	AUTEC	Simulated MFA	2007	Blainville's beaked whale	138	NA	> 1
#7 – no ID	AUTEC	Pseudo-random noise	2008	Blainville's beaked whale	142	NA	> 1

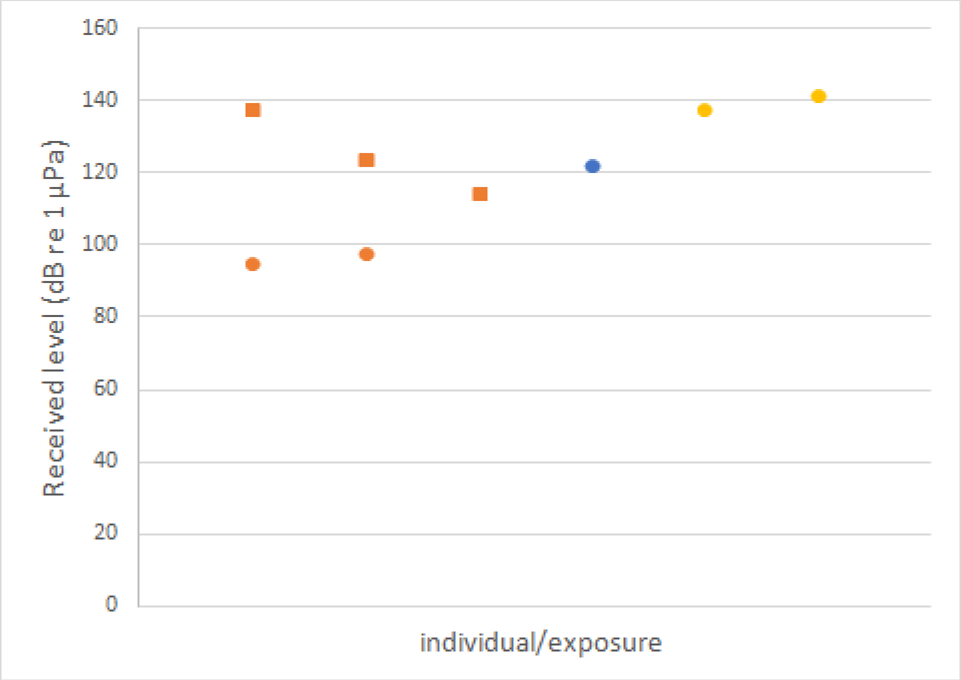

Figure 3-9. Received levels of Beaked Whale responses (in circles) or maximum received levels when there was no response (in squares). BRS Cuvier's and Baird's beaked whales are in orange, 3S bottlenose whale is in light blue, AUTEC Blainville's beaked whales are in yellow.

In order to equally weight the contributions from the eight exposures in the BRS and 3S field studies and the Moretti et al. (2014) GAM data, the GAM was sampled eight times equally across the curve (e.g., the curve was subsampled at eight equally spaced probabilities to get the corresponding received levels). Since the Moretti et al. (2014) data only extends to 180 dB re 1 µPa with a 95% probability of response, the beaked whale curve was right-censored with a probability of 100% response at 185 dB re 1 µPa based on the bottlenose dolphin and California sea lion Controlled Exposure Studies (Houser et al., 2013a, 2013b), similarly to what was done for the Mysticete BRF derived above. The risk function resulting in the combination of these data sets and presented here had a 50% probability of response at 144 dB re 1 µPa (Figure 3-10).

Although the Moretti et al. (2014) data is different than other data used here in the derivation of the other behavioral response functions, without its use to fill in responses at higher received levels, the dose functions will be fit based solely on low to moderate level exposures from proximal sources such as most of those from the BRS/3S2 datasets. This would violate standard dose response methodology, mainly, that a sufficient range of "doses" are provided to define a range of responses from 0-100% (or at least most of the range). The Moretti et al. (2014) curve provides "observations" of the proportions responding at higher received levels. Additionally, as discussed above, these observations were during actual multi-ship, multi-day ASW events on AUTEC.

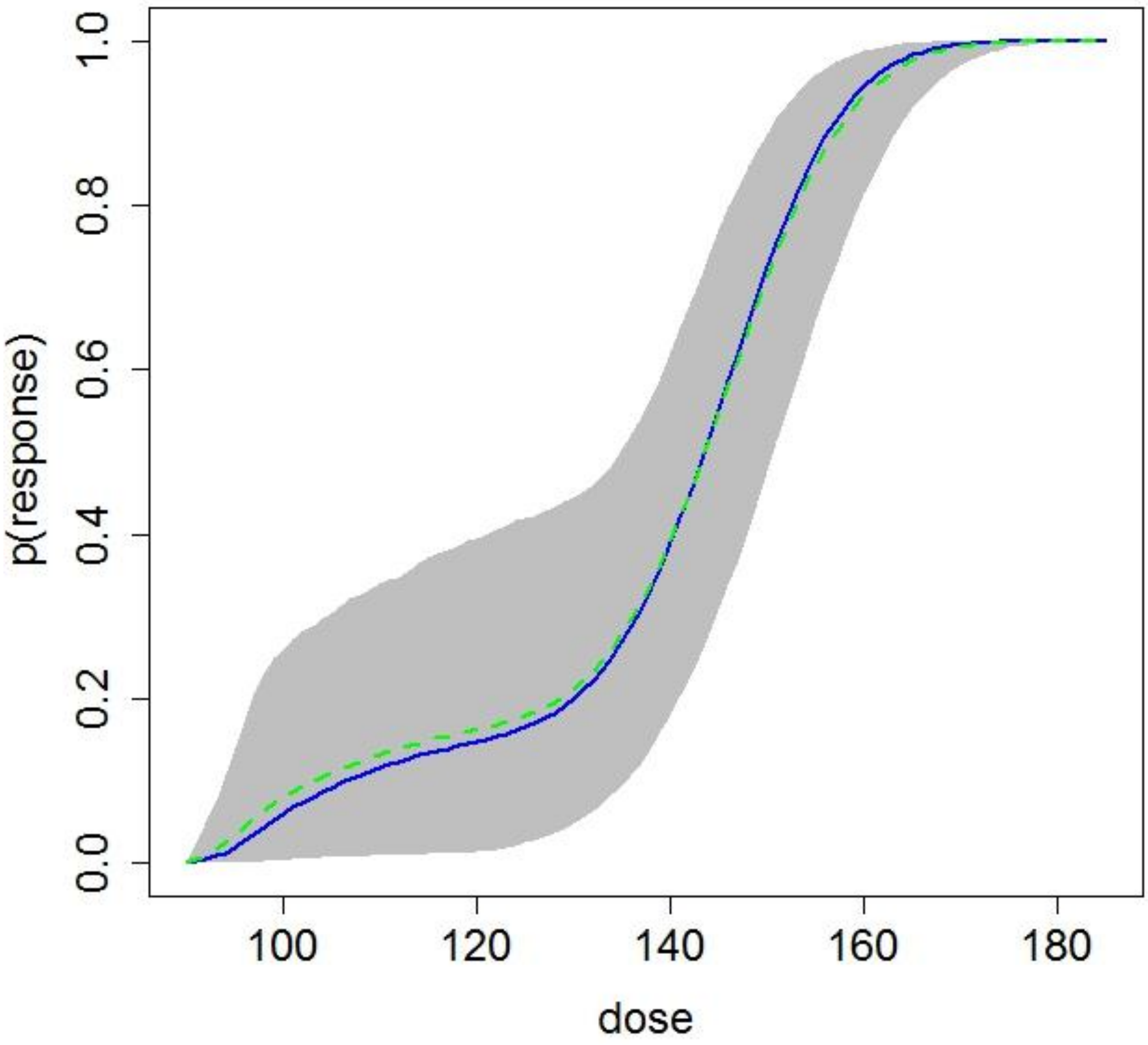

Figure 3-10. The Bayesian biphasic dose-response BRF for Beaked Whales. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

3.1.8.7 Harbor Porpoise

For harbor porpoises, the information currently available suggests a very low threshold level of response for both captive and wild animals. Received SPLs at which both captive (Kastelein et al., 2000; Kastelein et al., 2005a) and wild harbor porpoises (Johnston, 2002) responded to sound (e.g., acoustic harassment devices, acoustic deterrent devices, or other non-impulsive sound sources) are very low, ranging between 100 and 148 dB re 1 μPa (Cox et al., 2001; Culik et al., 2001; Kastelein et al., 1995; Kastelein et al., 2000; Kastelein et al., 2006b; Kastelein et al., 2008; Kastelein et al., 2012c; Kastelein et al., 2014a; Kastelein et al., 2014b; Kastelein et al., 2015c; Kastelein et al., 2015e; Kastelein et al., 2015f; Olesiuk et al., 2002; Teilmann et al., 2006). Kastelein et al. (2013c) investigated harbor porpoise behavioral responses to helicopter dipping sonar (1.33 – 1.43 kHz) with a 1.25 second pulse duration. They noted brief behavioral responses with a 50% point between 124 and 140 dB re 1 μPa. From the study, it is difficult to ascertain if these sound levels would elicit significant responses in wild harbor porpoises; although it is an indication that these animals are likely sensitive to lower levels of sound.

Thus, as in prior Navy analysis, a step function at an SPL of 120 dB re 1 μPa is used for harbor porpoises as a threshold to predict potential significant behavioral responses. This would be coupled with the cutoff distances for harbor porpoises discussed below in Section 0.

3.1.8.8 Sirenians (Manatees and Dugongs)

Due to a lack of specific data regarding sirenian reactions to sonar and other transducers, the mysticete BRF will be used as a proxy. Both mysticetes and manatees have demonstrated similar reactions to vessel noise and although distant, mysticetes are the most closely related marine mammal group. The Navy believes that the mysticetes behavioral response function is likely to capture the vast majority of potential significant behavioral responses in sirenians.

3.1.8.9 Sea Turtles

Sea turtle behavioral criteria for sonar and other transducers was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to sonar and other transducers.

Per discussions with NMFS, the received sound level at which sea turtles are expected to actively avoid air gun exposures, *175 dB re 1 μPa SPL rms* (McCauley et al., 2000), is also expected to be the received sound level at which sea turtles would actively avoid exposure to sonar and other transducers during Navy training and testing activities. This behavioral threshold will be applied to sources up to 2 kHz.

3.1.9 Application of Contextual Factors - Distance Cutoffs

During the Phase I and II analysis, propagation loss estimates to the BRFs basement level of 120 dB re 1 μPa sometimes extended to over 150 km from the most powerful sonar sources (e.g., AN/SQS-53). At these distances, it is likely that the context of the exposure is more important than the amplitude; in other words, the context-based response dominates the level-based response. As discussed above, an important contextual factor is the distance between the animal and the sound source.

In the Phase III analyses, the Navy will use distance cutoffs beyond which the potential of significant behavioral responses is considered to be unlikely. For animals located beyond the distance cutoff, no significant behavioral responses will be predicted. For animals within the distance cutoff, a behavioral response function based on a received SPL as presented in Section 3.1.0 is used to predict the probability of a potential significant behavioral response. For training and testing events that contain multiple platforms or tactical sonar sources that exceed 215 dB re 1 μPa @ 1 m, this cutoff distance is substantially increased (i.e., doubled) from values derived from the literature. The use of multiple platforms and intense sound sources are factors that probably increase responsiveness in marine mammals overall. There are currently few behavioral observations under these circumstances; therefore, the Navy will conservatively predict significant behavioral responses at further ranges for these more intense events.

3.1.9.1 Odontocetes (excluding beaked whales and harbor porpoises)

When reviewing sonar and seismic survey marine mammal monitoring literature, no significant behavioral reactions have been observed beyond a few kilometers. Weir (2008) reports on a large scale seismic survey (5,085 cu. in. and 3,147 cu. in. arrays) conducted over a 10 month period off the African coast, in which spotted dolphins (*Stenella frontalis*) avoided the source by 0.5 to 1 km during firings. In contrast, when the air guns were not firing, dolphins were seen near vessels often to bowride.Similarly Stone and Tasker (2006) reported the median sighting distance increased for all species except sperm whales from about 0.5–1.0 km without shooting to about 1.0 – 2.0 km with shooting; sperm whales tended to decrease their median distance from about 2 km with no shooting to under 1.5 km with shooting underway. These data covered observations for over 200 surveys (over 45,000 hours of survey effort) with seismic airgun arrays ranging from 180 – 3,000 cu. in.

The 3S and BRS sonar playback studies were largely conducted within about 8 km, so it is difficult to extrapolate to the distance at which odontocetes are not likely to respond. However, during the most recent BRS field seasons, researchers were able to coordinate with Navy ships to expose tagged Risso's dolphins (*Grampus griseus*) to actual mid-frequency sonar. These distances were on the order of tens of kilometers, and no responses were observed (Southall et al., 2014; Southall pers. comm. 2014).

These data suggest that most odontocetes (not including beaked whales and harbor porpoises) likely do not exhibit significant behavioral reactions to sonar and other transducers beyond approximately 10 km; therefore*, the distance cutoff for odontocetes will be 10 km for moderate source level, single platform training and testing events; and 20 km for all other events with multiple sonar platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.*

3.1.9.2 Mysticetes

During 3S exposures to humpback whales (pers. comm. P. Miller, Dec 2014) animals that reacted were within about 1 km, although most of the sonar exposures began at 1-2 km from the whale. Similarly, during BRS exposures to blue whales, responses occurred when the source was within 2 km (pers. Comm. B. Southall, Dec 2014). During Phase I of LFA playbacks, no responses by either blue or fin whales were observed; in one case a whale swam past the transmitting vessel in the direct path of the playback at a range of 200 - 300 m. During Phase II of LFA playbacks, migrating gray whales avoided the source by 500 - 2000 m when it was placed near the center of their migratory path; however, when the source was moved approximately 2 km further offshore, the animals no longer altered their paths (Buck & Tyack, 2000; Clark et al., 1999; Ellison et al., 2011).

Preliminary results from passive acoustic monitoring on the Pacific Missile Range Facility found three interactions between Navy ships and minke whales. The first minke whale was 15 km away when a ship began transmitting sonar, and was about 9 km away when it stopped vocalizing (~15 min later). The ship was heading directly towards the minke's position in that case. A second whale was about 17 km away from a ship, and rather than being in the ship's path was off to the side; in this case the ship moved away from the whale and the whale kept vocalizing. Finally, a third whale was about 9 km from a ship that was not transmitting sonar but was approaching the whale, and the whale stopped calling (Martin et al., 2015). It should be noted that a change in vocalization is not necessarily a significant behavioral response by itself, although it could be indicative of moderate severity responses such as interrupting feeding or mating behavior. In this case it is an indicator that reactions beyond 10 km have not been acoustically detected in these very limited results.

It is important to note that these are the distances within which behavioral responses have been observed, which is decoupled from the acoustic habitat or communication space that these large whales likely utilize. While their low frequency vocalizations may be detected across tens to hundreds of kilometers, their behavioral responses to low- and mid-frequency active sonar seem to be limited to within 10 km.

The available data suggest that mysticetes likely do not exhibit significant behavioral reactions to sonar and other transducers beyond about 10 km; *therefore, the distance cutoff for mysticetes will be 10 km for moderate source level, single platform training and testing events; and 20 km for all other events with multiple sonar platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.*

3.1.9.3 Pinnipeds

Southall et al. (2007) report that pinnipeds do not exhibit strong reactions to SPLs up to 140 dB re 1 µPa from steady state (non-impulsive) sources. In some cases, pinnipeds tolerate impulsive exposures up to 180 dB re 1 µPa with limited avoidance noted (Southall et al., 2007), and no avoidance noted at distances as close as 42 m (Jacobs & Terhune, 2002). There are still limited data on pinniped behavioral responses beyond about 3 km in the water.

The available data suggest that most pinnipeds likely do not exhibit significant behavioral reactions to sonar and other transducers beyond a few kilometers, independent of received levels of sound; *therefore, the distance cutoff for pinnipeds will be 5 km for moderate source level, single platform training and testing events; and 10 km for all other events with multiple sonar platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.*

3.1.9.4 Beaked Whales

During an actual Navy training event at AUTEC in Andros Bahamas, Blainville's beaked whales moved an average of 16 km from the sonar transmissions (Tyack et al., 2011). During sonar and pseudorandom noise playbacks at AUTEC, a Blainville's beaked whale responded by breaking off a feeding dive and ascending slowly. This animal received SPLs of approximately 140 dB re 1 µPa from a projector located about 1 km from its dive location (Boyd et al., 2009; Tyack et al., 2011). During playback experiments of simulated sonar and pseudorandom noise off the coast of SOCAL, Cuvier's beaked whales reacted to SPLs between 89 and 127 dB re 1 µPa by swimming rapidly and silently away from the source. The sound projector was located within 3 km of the whales diving location. In contrast, actual sonar exercises at a distance of approximately 118 km with SPLs at the whales of 78 to 106 dB re 1 µPa did not elicit the same reactions (DeRuiter et al., 2013). Likewise, in recent observations during the SOCAL behavioral response study, beaked whales showed no observable response to actual hull-mounted ASW sonar at distances of 60 to 75 km (pers. comm. B. Southall 2014). Recent analyses of possible Blainville's beaked whale behavioral responses to Navy sonar at the Pacific Missile Range Facility found cessation of clicks to occur when ships were between 10 to 35 km and typically approaching the location of the group. Groups continued to click when ships were between 25 and 40 km and typically heading away from the location of the group (Henderson et al., 2016).

These data suggest that most beaked whales likely do not exhibit significant behavioral reactions to sonar and other transducers beyond approximately 20 km; therefore, *the distance cutoff for beaked whales will be 25 km for moderate source level, single platform training and testing events; and 50 km for all other events with multiple sonar platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.*

3.1.9.5 Harbor Porpoises

There are no data available on the reaction distances of harbor porpoises to sonar or other transducers; however, movement patterns of harbor porpoises have been studied during pile driving to install wind turbines in European waters (Dähne et al., 2014; Tougaard et al., 2009). These studies have shown that harbor porpoises are displaced within about 20 km of the activity area.

These data suggest that most harbor porpoises likely do not exhibit significant behavioral reactions to sonar and other transducers beyond approximately 20 km; therefore, *the distance cutoff for harbor porpoises will be 20 km for moderate source level, single platform training and testing events; and 40 km for all other events with multiple platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.*

3.1.9.6 Sirenians

No applicable data on reaction distances for manatees or dugongs from sonar or other transducers is available. Manatees responded to boat approaches at 25 - 50 m (Nowacek et al., 2004b) and during playback of vessel approaches, showed a higher probability of reaction with increased speed of approach (Miksis-Olds et al., 2007). There is limited overlap between sirenian habitat and areas where the Navy would train and test. Many of these areas are confined inland waterways (e.g., Naval Station Mayport) where cutoff distances would exceed the size of the ensonified area. Therefore, cutoff distances for manatees would be difficult to ascertain and are not really applicable in smaller inland areas. Therefore, as there were no data available from which to develop cutoff distances, mysticete distances will be used in place.

As with mysticetes, the distance cutoff for sirenians will be 10 km for moderate source level, single platform training and testing events; and 20 km for all other events with multiple platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.

3.2 Behavioral Response Thresholds for Air Guns

3.2.1 Marine Mammals

Existing National Marine Fisheries Service risk criteria are applied to the unique sounds generated by air guns at 160 dB re 1 µPa (rms). The root mean square calculation for air guns driving is based on the duration defined by 90 percent of the cumulative energy in the impulse.

3.2.2 Sea Turtles

Sea turtle behavioral criteria was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to air guns.

During two air gun exposure studies (McCauley et al., 2000; O'Hara & Wilcox, 1990), sea turtles were exposed to air gun shots over long durations (approximately 30 minutes of a traveling air gun and greater than 20 hours of a stationary air gun, respectively). From these studies, (McCauley et al., 2000) hypothesized that sea turtles would actively avoid repeated air gun shots at received levels of 175-176 dB re 1 µPa rms.

Per discussions with NMFS, a threshold of 175 dB re 1 µPa SPL(rms*)* is applied to estimate sea turtle behavioral reactions to repeated air gun firing during Navy testing activities. The root mean square calculation for air guns is based on the duration defined by 90 percent of the cumulative energy in the impulse.

3.3 Behavioral Response Thresholds for Pile Driving

3.3.1 Marine Mammals

Existing NMFS risk criteria are applied to estimate behavioral effects from impact and vibratory pile driving (Table 3-8). The root mean square calculation for impact pile driving is based on the duration defined by 90 percent of the cumulative energy in the impulse.

Table 3-8. Pile Driving Level B Thresholds Used in this Analysis to Predict Behavioral Responses from Marine Mammals.

Underwater Vibratory Pile Driving Criteria (Sound Pressure Level, dB re 1 µPa) Level B Disturbance Threshold	Underwater Impact Pile Driving Criteria (Sound Pressure Level, dB re 1 µPa) Level B Disturbance Threshold
120 dB rms	160 dB rms

dB: decibel; dB re 1 µPa: decibel referenced to 1 micro pascal; rms: root mean square

Note: Root mean square calculation for impact pile driving is based on the duration defined by 90 percent of the cumulative energy in the impulse. Root mean square for vibratory pile driving is calculated based on a representative time series long enough to capture the variation in levels – usually on the order of a few seconds.

3.3.2 Sea Turtles

Sea turtle behavioral criteria for impact and vibratory pile driving was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). Impact pile driving produces repetitive, impulsive sounds potentially over multiple minutes, similar to repeated air gun shots. In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to pile driving.

Per discussions with NMFS, the received sound level at which sea turtles are expected to actively avoid air gun exposures, 175 dB re 1 µPa SPL (rms) based on studies of sea turtles exposed to air guns (McCauley et al., 2000; O'Hara & Wilcox, 1990), is also expected to be the received sound level at which sea turtles would actively avoid exposure to impact pile driving noise during Navy training activities. Additionally, 175 dB re 1 µPa SPL (rms) is expected to be the received sound level at which sea turtles would actively avoid exposure to vibratory pile driving noise during Navy training activities. The root mean square calculation for impact pile driving is based on the duration defined by 90 percent of the cumulative energy in the impulse.

3.4 Behavioral Response Thresholds of Explosives

3.4.1 Marine Mammals

If more than one explosive or explosive cluster is detonated within any given 24-hour period during a training or testing activity, criteria are applied to predict the number of animals that may have a behavioral reaction. For events with multiple explosions, the behavioral threshold used in this analysis is

5 dB less than the TTS onset threshold (See Table C.6 in Appendix C). This value is derived from observed onsets of behavioral response by test subjects (bottlenose dolphins) during non-impulse TTS testing (Schlundt et al., 2000).

Some multiple explosive events, such as certain naval gunnery exercises, may be treated as a single event because a few explosions occur closely spaced within a very short time (a few seconds). For single explosions at received sound levels below hearing loss thresholds, the most likely behavioral response is a brief alerting or orienting response. Since no further sounds follow the initial brief impulses, significant behavioral reactions would not be expected to occur. This reasoning was applied to previous shock trials (63 FR 230; 66 FR 87; 73 FR 143) and is extended to the criteria used in this analysis.

3.4.2 Sea Turtles

Sea turtle behavioral criteria for explosives was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to explosives.

Sea turtles are assumed to exhibit no more than a brief startle response to any individual explosive or explosive cluster. If an event has longer duration use of explosives, such as some gunfire events with multiple clusters of explosive shells, a sea turtle is may exhibit a response beyond an initial startle, such as actively avoiding the area. Unlike long duration air gun exposures described in Section 3.2.2 (Air guns - Sea Turtles) in which sea turtles were exposed to many regular, repeated firings (number of firings equal to about 100 or much greater), most explosive events do not consist of a high number of regular, repeated shots. Rather, they consist of irregularly spaced detonations (in space and time) that, on their own, may only result in startle responses.

Per discussions with NMFS, the received sound level at which sea turtles are expected to actively avoid air gun exposures, *175 dB re 1 μPa SPL rms* based on studies of sea turtles exposed to air guns (McCauley et al., 2000), is also expected to be the received sound level at which sea turtles would actively avoid events with multiple explosions during Navy training and testing activities.

4 EXPLOSIVE NON-AUDITORY INJURY CRITERIA

4.1 Introduction

This section describes the criteria for estimating non-auditory physiological impacts on marine mammals and sea turtles due to naval underwater explosions. These criteria follow a similar methodology as past Navy explosive impact analyses (Finneran & Jenkins, 2012b; U.S. Department of the Navy, 2001, 2008), while refining the approach to take advantage of current modeling capabilities. Impact thresholds are defined for both the estimate of quantitative effects for impact analyses (i.e., 50 % effect) and the estimate of onset of effect for analysis of mitigation zones (e.g., 1% effect).

The effects of underwater explosions on marine mammals and sea turtles depend on a variety of factors including animal size and depth; charge size and depth; depth of the water column; and distance between the animal and the charge. The gas-containing organs (lungs and gastrointestinal tract) are most vulnerable to primary blast injury. Severe injuries to these organs are presumed to result in mortality (e.g., severe lung damage may introduce air into the cardiopulmonary vascular system, resulting in lethal air emboli).

Because gas-containing organs are more vulnerable to primary blast injury, adaptations for diving that allow for collapse of lung tissues with depth may make animals less vulnerable to lung injury with depth. Adaptations for diving include a flexible thoracic cavity, distensible veins that can fill space as air compresses, elastic lung tissue, and resilient tracheas with interlocking cartilaginous rings that provide strength and flexibility (Ridgway, 1972). Older literature suggested complete lung collapse depths at approximately 70 m for dolphins (Ridgway & Howard, 1979) and 20-50 m for phocid seals (Falke et al., 1985; Kooyman et al., 1972). Follow-on work by (Kooyman & Sinnett, 1982), in which pulmonary shunting was studied in harbor seals and sea lions, suggested that complete lung collapse for these species would be about 170 m and about 180 m, respectively. More recently, evidence in sea lions suggests that complete collapse might not occur until depths as great as 225 m; although the depth of collapse and depth of the dive are related, sea lions can affect the depth of lung collapse by varying the amount of air inhaled on a dive (McDonald & Ponganis, 2012) This is an important consideration for all divers which can modulate lung volume and gas exchange prior to diving via the degree of inhalation and during diving via exhalation (Fahlman et al., 2009). Indeed, there are noted differences in pre-dive respiratory behavior with some marine mammals exhibiting pre-dive exhalation to reduce the lung volume [e.g., phocid seals (Kooyman et al., 1973)].

4.2 Data on underwater blast injury to marine mammals and sea turtles

Data on blast injury to marine mammals and sea turtles is limited. Richardson et al. (1995) summarized past exposures and evidence of mortality or injury to wild marine mammals; animal proximity to explosions was generally not available, and the amount of data was overall insufficient to define injury criteria.

Since Richardson et al.'s (1995) summary, there has been one documented incident of mortalities to marine mammals after exposure to an explosion during Navy training. In 2011, three long-beaked common dolphins were immediately killed by exposure to a 3.97-kg net explosive weight charge placed on the seafloor in 48 feet (15 m) of water during an underwater detonation training activity at the Silver

Strand Training Complex near San Diego, CA [for additional information, see Danil & St. Ledger (2011)]. A fourth long-beaked common dolphin was found on-shore dead three days after the detonation with injuries consistent with blast exposure. The dolphins were in a pod of about 100-150 dolphins that swam into the mitigation zone preceding the detonation. The explosive device was set on a time-delay fuse, and attempts to deter the animals' travel toward the detonation site were unsuccessful. Although the animals were seen approaching the blast area, the actual locations of the injured animals relative to the charge at the time of detonation are unknown. Upon necropsy, all four animals were found to have sustained typical mammalian primary blast injuries (Danil & St. Ledger, 2011).

Incidental impacts on sea turtles were documented for exposure to a single 1200-lb (540 kg) underwater charge off Panama City, FL in 1981. The charge was detonated at mid-depth in water 120 feet (37 m) deep. Although details are limited, the following were recorded: at a distance of 500-700 ft. (150-200 m), a 400 lb. (180 kg) sea turtle was killed; at 1200 ft. (370 m), a 200-300 lb. (90-140 kg) sea turtle experienced "minor" injury; and at 2000 ft. (600 m) a 200-300 lb. (90-140 kg) sea turtle was not injured (O'Keeffe & Young, 1984).

4.3 Data on underwater blast injury to terrestrial mammals

Due to the scarcity of marine mammal data, development of explosive impact criteria relies on data from exposures of terrestrial animals to controlled underwater blasts. In the early 1970s, the Lovelace Foundation for Medical Education and Research conducted a series of tests in an artificial pond at Kirtland Air Force Base, NM to determine the effects of underwater explosions on mammals, with the goal of determining safe ranges for human divers. During the tests, sheep, dogs, and monkeys were positioned at or near the water surface at 1, 2, and 10 ft. (0.3, 0.6, and 3 m) depths and at varying distance from charges in a large pool. Animals at 10 ft. depth were attached to a pressurized underwater breathing apparatus. Charges ranged from 0.5 to 8 lb. (0.23 to 6.3 kg) of pentolite and/or TNT placed at 10 ft. (3 m) depth. No deaths were observed from blast injuries. Mammals were sacrificed two hours after exposure, and damage to the lungs and gastrointestinal (GI) tract were examined. Acoustic impulse was found to be the metric most related to degree of injury, and size of an animal's gas-containing cavities was thought to play a role in blast injury susceptibility (Richmond et al., 1973; Yelverton et al., 1973). The subject animals were exposed near the water surface; therefore, depth effects were not discernible in this data set. The resulting data were summarized in two reports (Richmond et al., 1973; Yelverton et al., 1973). For these shallow exposures of dogs, sheep, and monkeys (masses ranging from 3.4 to 50 kg) to underwater detonations, Richmond et al., 1973 (1973) reported that:

- An impulse of 34 psi-ms (230 Pa-s) resulted in about 50% incidence of slight lung hemorrhage. Below 20 psi-ms (140 Pa-s) there were no instances of slight lung hemorrhage.
- Some exposures at higher levels (up to 40 psi-ms [280 Pa-s]) resulted in no observable lung damage.
- About half of the animals had gastrointestinal tract contusions (with slight ulceration, i.e., some perforation of the mucosal layer) at exposures of 25-27 psi-ms (170-190 Pa-s). Lung injuries were found to be slightly more prevalent than GI tract injuries for the same exposure level.

Specific physiological observations for each test animal are documented in Richmond et al. (1973).Some limitations of this dataset are (Richardson et al., 1995):

- Subjects were held at shallow depths or at the surface.
- Test animals were small compared to the range of marine mammal sizes.
- Only injuries evident at sacrifice/necropsy at two hours after exposure were considered (i.e., longer term survival rates were not considered).
- Lungs were expanded at depth because the animals were actively breathing air (unlike breath-hold divers).

Additionally, some control animals connected to the underwater breathing apparatus but not exposed to detonations exhibited lung damage or died. It is reasonable to assume that in some instances lung damage observed in animals exposed to detonations may have been exacerbated by animal handling procedures or the underwater life support system.

While the above study was conducted to assess safe ranges for human swimmers, it is the best available data set for assessing non-auditory physiological impacts on marine mammals and sea turtles from explosives. The lungs of marine mammals are grossly similar in proportion to overall body size as those of terrestrial mammals, so the magnitude of lung damage in the tests may approximate the magnitude of injury to marine mammals when scaled for body size. However, within the marine mammals, (Piscitelli et al., 2010) observed that mysticetes and deeper divers (e.g., Kogiidae, Physeteridae, Ziphiidae) tend to have lung to body size ratios that are smaller and more similar to terrestrial animal ratios than shallow diving odontocetes (e.g., Phocoenidae, Delphinidae). Measurements of some shallower diving sea turtles (Hochscheid et al., 2007) and pinnipeds (Fahlman et al. 2014) show lung to body size ratios that are similar to shallow diving odontocetes, whereas the lung to body mass ratio of the deeper diving leatherback sea turtle is smaller (Lutcavage et al., 1992). The use of test data with smaller lung to body ratios results in a more conservative estimate of potential for damaging effects (i.e., lower thresholds).

Yelverton & Richmond (1981) conducted probit analyses of the Lovelace Foundation injury data and mortality data (i.e., extensive lung injury discovered after animals were sacrificed and necropsied, as no mortalities were observed in two-hour observation period post exposure) (Richmond et al., 1973; Yelverton et al., 1973), relating likelihood of injury to impulse. The probit analyses were used to develop regression equations for 50% mortality and 1% mortality relating impulse to body mass for shallow water exposures (see Figure 4-1):

$$\text{50\% mortality: } \ln(I) = 4.938 + 0.386 \ln(M) \qquad (1)$$

$$\text{1\% mortality: } \ln(I) = 4.507 + 0.386 \ln(M) \qquad (2)$$

where: I = impulse threshold for effect (Pa-s)
M = animal mass (kg)

A parallel No Injury equation was developed based on the highest impulse below which no injuries were observed:

No Injury: $\ln(I) = 3.888 + \ln(M)$ (3)

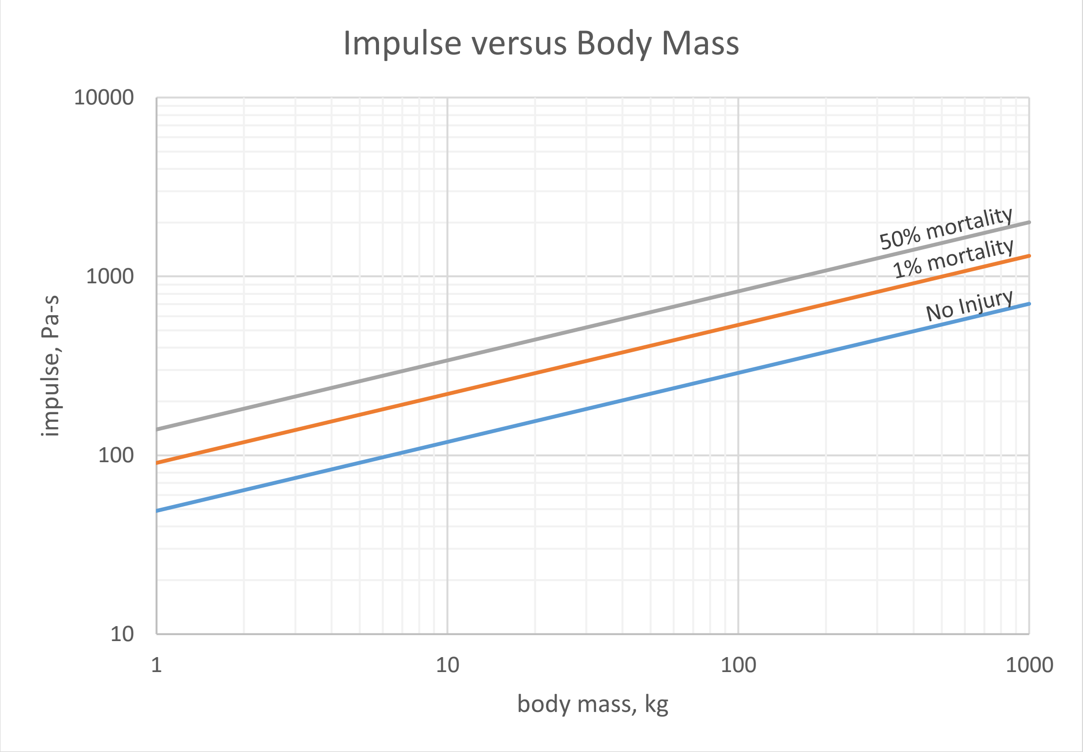

Figure 4-1. Relationships between impulse threshold for effect and body mass as derived in Yelverton & Richmond (1981) based on the Lovelace Foundation test results for terrestrial animals exposed to underwater detonations.

4.4 Goertner Lung injury model

The above regression equations do not account for how an animal could be affected with increasing depth. Goertner (1982) examined how lung cavity size would affect susceptibility to blast injury by considering both animal size and animal depth. Animal depth relates to injury susceptibility in two ways: injury is related to the relative increase in explosive pressure over hydrostatic pressure, and lung collapse with depth reduces the potential for air cavity oscillatory damage. Goertner (1982) estimated the oscillation period of the lung air cavity based on animal size and depth (i.e., hydrostatic pressure).

4.4.1 Impulse Duration for Injury

Goertner (1982) assumed that the impulse necessary to cause lung damage is related to the amplitude of lung oscillations and must be delivered over a specified time period. To account for long duration positive pressures, such as could occur with broadening of the initial positive pressure pulse with shock wave decay, the concept of “partial impulse” is applied, described by (Bowen et al., 1968) as the impulse occurring over the time duration leading to maximum gas cavity compression. This duration is the lesser of the duration of the initial positive pressure or 20% of the estimated lung resonance period (T). To determine the lung resonance period, the lung is modeled as a spherical gas bubble. As such, the oscillation period of the lung shortens with increasing hydrostatic pressure as the bubble (lung) collapses. Ultimately, a depth is reached where sufficient impulse cannot be delivered during the shortened period to result in an injurious effect. Because this model does not account for damping of lung response by the surrounding tissues, it considers a maximum lung compressive response.

The derivation of the equation to estimate lung resonance period is described in Goertner (1982). When all substitutions are made, the reduced equation is:

$$T = 22.5\, M^{1/3} \frac{p_{atm}^{1/3}}{p_{hyd}^{5/6}} \tag{4}$$

where: M = animal mass (kg)
p_{hyd} = hydrostatic pressure (psi)= p_{atm} + (γ_wD/144)
p_{atm} = atmospheric pressure (psi)
γ_w = specific weight of water (lb/ft^3)
D = depth of animal (ft)

The steep-front, high-amplitude shock wave is the initial positive pressure amplitude used to calculate impulse exposure for damaging effect. The shock wave caused by an explosion in deeper water may be followed by several bubble pulses with lower peak pressures (about one-fifth the initial peak pressure for the first follow-on pulse) and lacking the steep pressure front of the initial explosive pulse (Urick, 1983). These bubble pulses are not considered when analyzing injury potential due to peak pressure or impulse, as these values are inherently lower for bubble pulse exposure than for initial exposure.

The impulse exposure would be affected by the depth of the charge and the depth of the receiving animal. If a charge is detonated closer to the surface or if an animal is closer to the surface, the time between the initial direct path arrival and the surface-reflected tension wave arrival is reduced, resulting in a steep negative pressure cut-off of the initial direct path impulse exposure. Two animals at similar distance from a charge, therefore, may experience the same peak pressure but different impulse at different depths.

4.4.2 Impulse Scaling for Animal Size and Depth

Goertner (1982) also developed a scaling parameter for impulse-based lung damage that relates impulse associated with an observed effect to animal size and ambient pressure (hydrostatic and atmospheric). Equation 2.9 in Goertner (1982) shows this relationship as follows (note that water density in the denominator is later dropped as a constant, so it is not shown here):

$$\frac{I}{A_D p_{hyd}^{1/2}} \tag{5}$$

where: I = impulse for onset of injury effect
A_D = lung (bubble) radius at depth, D

Air bubble size (as proxy for lung size) decreases with increasing hydrostatic pressure at depth per Boyle's Law:

$$A_D = A_{atm}\left(\frac{p_{atm}}{p_{hyd}}\right)^{1/3} \tag{6}$$

where: A_{atm} = lung radius at the surface

Substituting Equation 6 into Equation 5 and assuming that lung radius is proportional to the cube root of body mass, the complete impulse scaling parameter is obtained:

$$\frac{I}{M^{1/3}\left(p_{atm}^{1/3}\right)\left(p_{hyd}^{1/6}\right)} \qquad \text{(Eqn. 7)}$$

This scaling parameter is used to develop impulse-based thresholds by substituting appropriate known values from test data (designated by subscript *t*) documented in Richmond et al. (1973), as follows:

$$\frac{I}{M^{1/3}\left(p_{atm}^{1/3}\right)\left(p_{hyd}^{1/6}\right)} = \frac{I_t}{M_t^{1/3}\left(p_{atm,t}^{1/3}\right)\left(p_{hyd,t}^{1/6}\right)} \qquad \text{(Eqn. 8)}$$

Solving for impulse (I) and substituting $p_{hyd} = p_{atm} + \gamma_w D$ results in the generalized Goertner lung injury scaling equation:

$$I = CM^{1/3}\left(1 + \frac{\gamma_w D}{p_{atm}}\right)^{1/6} \qquad \text{(Eqn. 9)}$$

$$\text{where: } C = I_t\left(\frac{p_{atm}^{1/2}}{M_t^{1/3}\, p_{atm,t}^{1/3}\left(p_{atm,t} + \gamma_{w,t} D_t\right)^{1/6}}\right) \qquad \text{(Eqn. 10)}$$

4.4.3 Impulse-based Injury Threshold Equations

Injury data from the animal exposures to underwater detonations documented in Richmond et al. (1973) are substituted into equations 9 and 10 to develop specific threshold equations for onset of slight lung injury and onset of mortality. The reference test data sets are for the animals that exhibited an effect (i.e., slight lung injury and extensive lung injury) at the lowest received impulse in the Lovelace experiments (see Table 4-1). There were numerous exposures in which animals received significantly higher impulses without either slight lung hemorrhage or extensive lung hemorrhage. In all cases, impulses at the test animals were received over a duration that was less than 20% of the lung resonance period.

Although no test animals died within two hours of blast exposure, longer-term survival rates were not studied. It is reasonable to assume for impact analysis that extensive lung hemorrhage is a level of injury that would result in wild animal mortality. Slight lung injuries, such as slight hemorrhage, are injuries from which an animal would be expected to survive.

The values for other environmental constants for the test and analysis conditions are shown in Table 4-2.

Table 4-1. Lowest test impulse exposure for injurious effects (Richmond et al., 1973).

Observed Effect	extensive lung hemorrhage (representative of onset mortality)	slight lung hemorrhage (i.e., onset slight lung injury)
Impulse, I_t	44.4 psi-ms (306 Pa-s)	22.8 psi-ms (157 Pa-s)
Animal Depth, D_t	2 ft.	10 ft.
Animal Mass, M_t	34 kg	42 kg

Table 4-2. Environmental constants.

Constant	***Value***
Atmospheric pressure at test site[1], $p_{atm,t}$	12 psi
Atmospheric pressure at sea level, p_{atm}	14.7 psi
Specific weight of fresh water[1], $\gamma_{w,t}$	62.4 lb/ft^3
Specific weight of sea water, γ_w	64 lb/ft^3

[1] Tests were conducted in a freshwater man-made pond. Richmond et al. (1973) reported the atmospheric pressure at the test site to be 12 psi.

Use of the above values results in threshold equations for onset mortality and onset slight lung injury (SLI) as follows:

$$I_{onset\ SLI} = 47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6} \text{ Pa-s} \qquad \text{(Eqn. 11)}$$

$$I_{onset\ mortality} = 103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6} \text{ Pa-s} \qquad \text{(Eqn. 12)}$$

where I = Impulse threshold (Pa-s)
D = depth of animal (m)

M = animal mass (kg)

Equation 1 is used as a starting point for developing a 50% mortality threshold equation that accounts for animal depth using the Goertner lung injury model. Using Equation 1, the near-surface threshold for 50% mortality would be 544 Pa-s for 34 kg animals.

A comparison between the test exposure with the lowest impulse associated with onset severe lung injury (i.e., onset mortality) shown in Table 4-1(M = 34 kg, I = 306 Pa-s) and the 1% mortality impulse threshold predicted by Equation 2 (the 1% mortality regression equation for the Lovelace shallow water explosive exposures) for a 34-kg animal (I = 354 Pa-s) shows that the test value is 14% lower than the value predicted using the regression equation. The 50% mortality threshold value predicted for a 34-kg animal using Equation 1, the 50% mortality regression equation for the Lovelace shallow water explosive exposures, is 544 Pa-s. To develop an impulse reference value to estimate a lower bound for 50% mortality consistent with the value for onset mortality, this prediction is lowered by 14% to 468 Pa-s. Using these reference values (I_t = 468 Pa-s, M_t = 34 kg) and the environmental values in Table 4-2, the Goertner lung injury threshold equation for 50% mortality is:

$$I_{50\%\,mortality} = 144M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6} \text{ Pa-s} \qquad \text{(Eqn. 13)}$$

Where: I = Impulse threshold (Pa-s)
D= depth of animal (m)
M = animal mass (kg)

To estimate the 50% slight lung injury impulse threshold using the Lovelace Foundation test data, a probit analysis was conducted using the sheep lung injury data (M_{avg} = 41 kg). The 50% response for lung injury corresponded to an exposure of 251 Pa-s. Following the procedure to conservatively estimate the 50% mortality reference point above, the 50% slight lung injury impulse threshold is reduced by 14% to estimate a lower bound of 216 Pa-s. Using these reference values (I_t = 216 Pa-s, M_t = 41 kg) and the environmental constants in Table 4-2, the Goertner lung injury threshold equation for 50% slight lung injury is:

$$I_{50\%\,slight\ lung\ injury} = 65.8M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6} \text{ Pa-s} \qquad \text{(Eqn. 14)}$$

4.5 Peak Pressure criterion

Peak pressure contributes to the “crack” or “stinging” sensation of a blast wave, compared to the “thump” associated with received impulse. High peak pressures can cause damaging instantaneous tissue distortion. Older military reports documenting exposure of human divers to blast exposure generally describe peak pressure exposures around 100 psi (237 dB re 1 µPa peak) to feel like slight pressure or stinging sensation on skin, with no enduring effects (Christian & Gaspin, 1974).

Goertner (1982) suggested a peak overpressure GI tract injury criterion because the size of gas bubbles in the GI tract are variable, and their oscillation period could be short relative to primary blast wave exposure. The potential for GI tract injury, therefore, may not be adequately modeled by the single oscillation bubble methodology used to estimate lung injury due to impulse. Like impulse, however, high instantaneous pressures may damage many parts of the body, but damage to the GI tract is used as an indicator of any peak pressure-induced injury due to its vulnerability.

In previous analyses, the peak pressure criterion was called the GI tract injury criterion because it is based on injury data for the vulnerable gas-containing organs of the gastrointestinal tract. Data from the Lovelace Foundation experiments show instances of GI tract contusions after exposures up to 1147 psi peak pressure, while exposures of up to 588 psi peak pressure resulted in many instances of no observed GI tract effects. As a vulnerable gas-containing organ, the GI tract is vulnerable to both high peak pressure and high impulse, which may vary to differing extents due to blast exposure conditions (i.e., animal depth, distance from the charge). This likely explains the range of effects seen at similar peak pressure exposure levels and shows the utility of dual injury criteria for explosives.

Examination of the GI tract contusion data versus peak pressure yields a 50% risk at 296 psi peak pressure (dose response fit, $R^2 = 0.56$). To reasonably estimate the number of animals that could be injured due to exposure to high peak pressures, and taking into account human diver exposures (see below), a peak pressure injury threshold of 200 psi (243 dB re 1 µPa peak) is used to quantify potential injuries. To account for injuries seen at some lower level exposures in the Lovelace data set, a peak pressure threshold of 104 psi (237 dB re 1 µPa peak) is used to inform mitigation.

4.6 Comparison to Human Diver Exposure Data

Data from human divers are informative as they provide subjective descriptions of sensations experienced during blast exposures. Human divers were voluntarily exposed to underwater detonations in order to develop safety standards for human divers. For a 165 lb. (75kg) human at 20 ft. (6 m) depth, the impulse thresholds for quantitatively assessing mortality and injury are 728 Pa-s and 333 Pa-s, respectively, using the impulse criteria described in this report. The peak pressure threshold for quantifying injury is 243 dB re 1 µPa peak (200 psi). The human diver exposures and impacts are described in

Table 4-3 and Table 4-4 below. The exposures that exceed the thresholds for quantifying injury are italicized. The exposures that exceed the threshold for quantifying mortality are bold. In these examples, the explosive injury criteria in no instance underestimate the potential for effect.

Table 4-3. Human diver blast exposure for 1.25-lb charge at 15-ft. depth, diver on bottom in 20 ft. water depth Wright et al. 1950 (as cited in Cudahy & Parvin, 2001).

Range (ft)	***Described Sensation***	***Estimated Peak Pressure (psi)***	***Estimated Impulse [psi-ms (Pa-s)]***
120	Loud bang. Slight pressure on torso but no discomfort.	85	29 (200)
90-75	Bang on head but no discomfort to ears or torso.	120-150	35-45 (240 – 310)
50	Intense bang. Blow on head and chest.	*240*	*65 (450)*
40	Severe blow on head and torso. Body violently shaken but no sub-sternal pain.	*300*	*76 (520)*
35	Strong blow on head and torso. Brief paralysis of arms and legs. Dull ache in chest. Brief sub-sternal pain.	*350*	*88 (610)*
32	Violent blow on head. Brief paralysis of limbs. Sub-sternal pain lasting several hours. Shattering sensation but no permanent injury.	*450*	***110 (760)***

Table 4-4. Human diver blast exposure for 5-lb charge at 15-ft. depth, diver on bottom in 20 ft. water depth Wright et al. 1950 (as cited in Cudahy & Parvin, 2001).

Range (ft)	**Described Sensation**	**Estimated Peak Pressure (psi)**	**Estimated Impulse [psi-ms (Pa-s)]**
110	Sound of intense bang.	160	*75 (520)*
100	Intense bang. Mild blow on chest.	175	*85 (590)*
90	Severe blow on chest.	195	*95 (660)*
80	Blow on head and torso. Body shaken. Brief paralysis of arms and legs.	*220*	*105 (720)*
75	Violent blow. Brief paralysis of limbs. Sub-sternal pain for 0.5-1 hour.	*240*	***110 (760)***
70	Violent blow. Temporary paralysis of limbs. Sub-sternal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	*260*	***115 (790)***

4.7 Summary

Two sets of thresholds are provided for use in non-auditory injury assessment. The first set provides thresholds to be used to estimate the number of animals that may be affected (see Table 4-5). The second set provides thresholds to estimate farthest range for potential occurrence of an effect and are for consideration in developing mitigation (see Table 4-6).

Table 4-5: Criteria to Quantitatively Predict Non-Auditory Injuries due to Underwater Explosions

Impact Assessment Criterion	Threshold
Mortality - Impulse	$144M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury - Impulse	$65.8M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury – Peak Pressure	243 dB re 1 µPa peak

Table 4-6: Onset of Effect Threshold for Estimating Ranges to Potential Effect

Onset effect for mitigation consideration	Threshold
Onset Mortality - Impulse	$103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury (Non-auditory) - Impulse	$47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury (Non-auditory) – Peak Pressure	237 dB re 1 µPa peak

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APPENDIX A. ESTIMATING A LOW-FREQUENCY CETACEAN AUDIOGRAM

A.1. Background

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

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

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

> (1) There are no peer-reviewed publications that provide a complete description of the mathematical process by which frequency-place maps based on anatomical measurements were integrated with models of middle-ear transfer functions and/or other information to derive the predicted audiograms presented in several settings by Ketten/Mountain (e.g. Ketten & Mountain, 2009). As a result, the validity of the resulting predicted audiograms cannot be independently evaluated, and these data cannot be used in the present effort.
>
> (2) Exclusion of the Ketten/Mountain predicted audiograms leaves only the Cranford/Krysl predicted fin whale hearing curve (Cranford & Krysl, 2015). However, this curve cannot be used by itself to predict hearing thresholds for all mysticetes because:
>
> (a) The Cranford/Krysl model is based on sound transmission through the head to the ear of the fin whale, but does not include the sensory receptors of the cochlea. There is therefore no way to properly predict the upper cutoff of hearing and the shape of the audiogram at frequencies above the region of best predicted sensitivity.
>
> (b) The audiogram does not possess the typical shape one would expect for an individual with normal hearing based on measurements from other mammals. Specifically, the “hump” in the low-frequency region and the shallow roll-off at high frequencies do not match patterns typically seen in audiometric data from other

> mammals with normal hearing. Given these considerations, the proposed audiogram cannot be considered representative of all mysticetes without other supporting evidence. Although the specific numeric thresholds from Cranford and Krysl (2015) are not directly used in the revised approach explained here, the predicted thresholds are still used to inform the LF cetacean composite audiogram derivation.

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

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

A.2. Audiogram functional form and required parameters

Navy Phase III composite audiograms are defined by the equation

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

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

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

where

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

and

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

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

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

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

which can also be written as

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

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

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

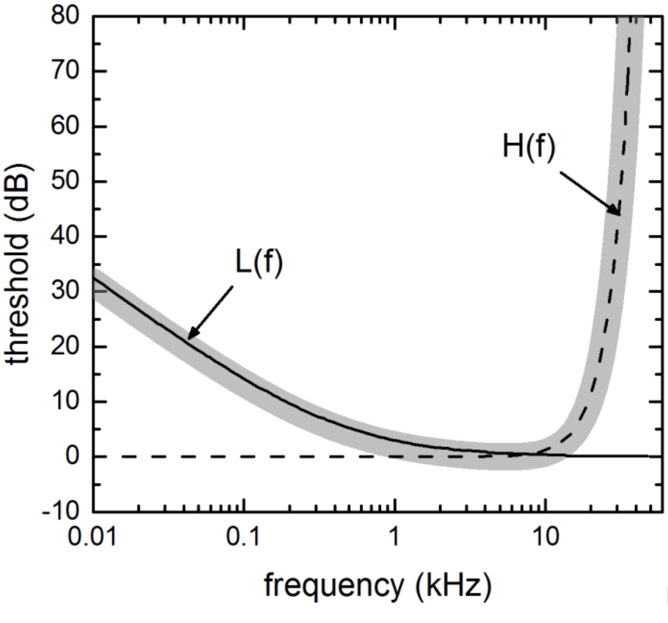

Figure A.1. Relationship between estimated threshold, T(f), (thick, gray line), low-frequency term, L(f), (solid line), and high-frequency term, H(f), (dashed line).

A.3. Estimating audiogram parameters

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

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

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

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

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

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

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

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

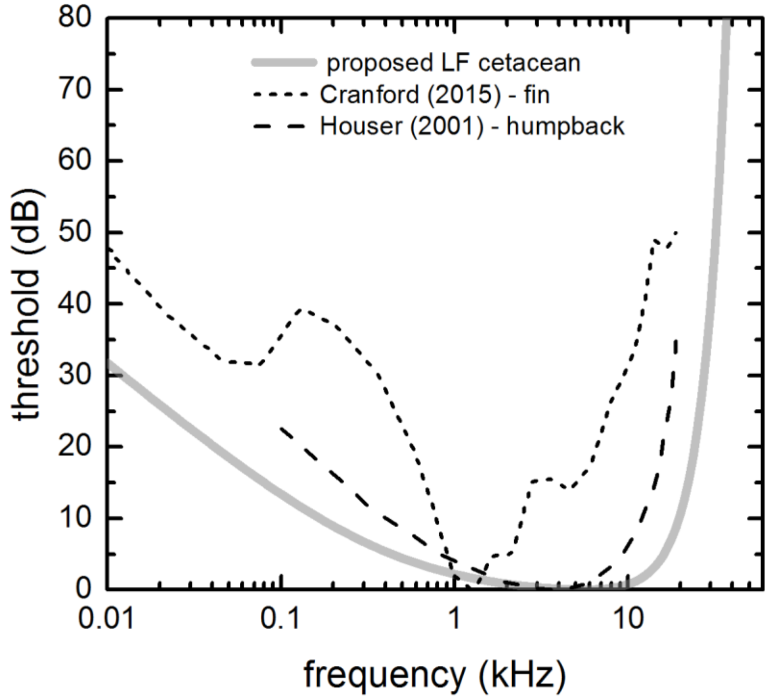

Figure A.2. Comparison of proposed LF cetacean thresholds to those predicted by anatomical and finite-element models.

APPENDIX B. DESCRIPTIONS OF BEHAVIORAL RESPONSES, RECEIVED LEVELS, DISTANCES, AND SEVERITY SCORING FOR DATA USED IN THE DEVELOPMENT OF THE PHASE III NAVY BRFS.

*Responses that are scored with an NDAA severity score of 1 were either of moderate severity and lasted as long as or longer than the duration of the exposure, or were of high severity; in either case they were determined to be significant behavioral responses***.** The distance from the animal to the source is given in km (when known); if the animal did not respond the closest point of approach (CPA) is reported. Exposure abbreviations are as follows: MFAS = Mid-frequency active sonar; LFAS = Low-frequency active sonar; Sonar1 = LFAS with ramp-up; Sonar2 = LFAS without ramp-up; PRN = pseudo-random noise.

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Killer whales - 3S							
oo06_317s	LFAS upsweep	Significant response was moderate avoidance and lasted the duration of the exposure.	145		4.5	6	1
oo06_327s/t	MFAS upsweep	Significant response was a change in behavioral state from foraging to travel, which lasted longer than the duration of the exposure. Additional responses included a change in group distribution and an increase in travel speed.	129		2.27	7	1
oo08_149a	MFAS upsweep	A brief/minor increase in call rate and change in speed were observed, did not rise to the level of a response.		142	1.5	3	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
oo08_149a	LFAS upsweep	A brief/minor modification in vocal response was observed, did not rise to the level of a response.		166	1.2	2	0
oo08_149a	MFAS upsweep	The significant response was the separation of a mother/calf pair, which lasted the duration of the exposure. Multiple additional responses were observed, including a change in direction of travel, a brief increase in travel speed, and an increase in vocalizations; all of these were likely subsequent to or concurrent with the mother/calf separation.	133		0.7	5	1
oo_09144a/b	LFAS upsweep	The significant response was an avoidance response that lasted longer than the duration of the exposure. This response included a change in behavioral state from foraging to travel, as well as a change in group distribution, an increase in vocalizations, and an increase in travel speed.	94.5		7.8	7	1

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
oo_09144a/b	MFAS upsweep	The significant response was an avoidance of the source which lasted the duration of or longer than the exposure period. Additional responses included a change in direction of travel, an increase in travel speed, and a change in group spacing/synchrony.	94		8.9	6	1
oo_09144a/b	LFAS downsweep	The significant response was an avoidance of the sound source that lasted the duration of the exposure. Additional responses included a change in direction of travel, an increase in travel speed, and a change in group spacing/synchrony.	161		3.2	6	1
Pilot whales - 3S							
gm08_150c	MFAS upsweep	The significant response included moderate avoidance, which lasted equal to the duration of the exposure. Additional responses included a cessation of vocalizations and mimicry.	114		6.2	6	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
gm08_150c	LFAS upsweep	There was an increase in vocalizations, increased travel speed, and a minor change in the direction of travel, these lasted less than the duration of the exposure and did not rise to the level of a response.		170	2.2	3	0
gm08_154d	MFAS upsweep	There was a brief cessation of vocalizations and a briefly increased travel speed; these did not rise to the level of a response.		152	0.23	1	0
gm08_159a	LFAS upsweep	There was a brief change in direction of travel, and a reduced travel speed that lasted less than the duration of exposure, and therefore did not rise to the level of a response.		175	1.2	3/4	0
gm08_159a	MFAS upsweep	No response was observed.		159	0.27	1	0
gm09_138a	LFAS upsweep	There was a brief decrease in travel speed and change in direction of travel which did not rise to the level of a response.		172	0.35	1	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 µPa)***	***Max RL Without a Response (dB re 1 µPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
gm09_138a	MFAS upsweep	There was a minor change in direction of travel which did not rise to the level of a response.		167	0.19	1	0
gm09_138a	LFAS downsweep	The significant response included a change in behavioral state from feeding to travel, and the response lasted the duration of the exposure.	145		0.09	6	1
gm09_156b	LFAS upsweep	The significant response included the cessation of feeding (cessation of deep dives) which lasted the duration of the exposure. Additional responses included a change in group spacing, a change in direction of travel, and an increase in vocalizations	152		3.11	5/7	1
gm09_156b	MFAS upsweep	There was a brief change in direction of travel and a moderate change in dive behavior that did not last the duration of the exposure and therefore did not rise to the level of a response.		156	0.32	4	0
gm09_156b	LFAS downsweep	The significant response was moderate avoidance that lasted the duration of the exposure.	152		3.37	6	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Sperm whales - 3S							
sw08_152a	MFAS upsweep	The significant response was moderate avoidance that lasted the duration of the exposure.	116		8.96	6	1
sw08_152a	LFAS upsweep	The significant response was a moderate cessation of feeding that lasted the duration of the exposure. In addition, there was a moderate change in vocal behavior.	156		NA	6	1
sw09_141a	LFAS upsweep	The significant response was moderate avoidance of sound source that lasted the duration of the exposure. Additional responses included brief-to-moderate changes in vocal behavior, and a brief change in dive profile.	151		3.3	6	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
sw09_141a	MFAS upsweep	There was moderate avoidance observed, as well as an increase in social sounds that represented a moderate change in vocalizations; however these did not last the duration of the exposure and therefore did not rise to the level of a response.		150	4.3	6	0
sw09_142a	LFAS upsweep	The significant response was an avoidance response that lasted the duration of the exposure. This response included a moderate change in dive behavior, and moderate change in direction of travel.	120		6.8	6	1
sw09_142a	MFAS upsweep	No response was observed.		146	1.8	0	0
sw09_142a	LFAS downsweep	The significant response was change in behavioral state from foraging to travel to rest, and a moderate change in dive behavior; these lasted the duration of the exposure. Other responses included a moderate change in vocal behavior, and a minor change in direction of travel.	139		8.2	6	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
sw09_160a	MFAS upsweep	No response was observed.		151	1.5	0	0
sw09_160a	LFAS upsweep	The significant response included a moderate change in dive behavior, and a change in behavioral state from foraging to travel; these lasted the duration of the exposure. Other responses included brief avoidance, and a moderate change in vocal behavior.	156		1.8	6	1
sw09_160a	LFAS downsweep	There was a brief avoidance at the closest point of approach, but this did not rise to the level of a response.		166	0.9	4	0
Humpback whales - 3S							
mn11_157	Sonar1	There was a brief avoidance when the animal turned away from the source, but was back again at the next sighting and therefore did not rise to the level of a response.		164	0.96	4	0
mn11_157	Sonar2	No response was observed.		177	0.06	0	0
mn11_160	Sonar1	No response was observed.		174	0.21	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
mn11_160	Sonar2	No response was observed.		168	0.42	0	0
mn11_165	Sonar1	No response was observed.		174	0.24	0	0
mn11_165	Sonar2	A minor change locomotion was observed when the animal made a sharp turn, but since it was not away from source, was not considered avoidance, and did not last the duration of the response, it did not rise to the level of a response.		175	0.2	3	0
mn12_161	Sonar1	Response included a moderate change in dive profile and moderate avoidance that included an increase in speed and a change in direction away from the source that lasted the duration of the exposure.	133		NA	6	1
mn12_161	Sonar2	There was a brief change in dive profile that only lasted for one dive then returned to normal during the exposure, and therefore did not rise to the level of a response.		167	0.44	2	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
mn12_164	Sonar1	Response included moderate cessation of feeding just after the onset of sonar, and an extended change in dive profile from deep to shallow dives; these lasted longer than the duration of the exposure.	125		0.83	6,5	1
mn12_164	Sonar2	There was a minor change in locomotion and a cessation of lunging coincided during the first dive of the exposure, but these did not rise to the level of a response.		170	0.02	3,4	0
mn12_170	Sonar1	Researchers thought there was a prolonged cessation of feeding, when one animal fed for little time before the sonar, then stopped, while the other animal did not feed at all. The feeding animals go back to feeding some time before the next sonar.	164		0.82	7	1
mn12_170	Sonar2	There was a minor avoidance that did not last the duration of the exposure, and therefore did not rise to the level of a response.		172	0.43	5	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
mn12_171	Sonar1	There was a minor change in dive profile from deep feeding dives to shallow dives and a minor cessation of feeding concurrent with that change, but these did not last the duration of the exposure and therefore did not rise to the level of a response.		179	0.19	3,5	0
mn12_171	Sonar2 (no ramp up)	There was moderate cessation of feeding observed, but it did not last the duration of the exposure and therefore did not rise to the level of the response.		182	0.06	6	0
mn12_178	Sonar1	There a brief avoidance away from the source, but it was difficult to determine whether this turn was in response to sonar, and did not last the duration of the exposure, and so did not rise to the level of a response.		174	0.48	4	0
mn12_178	Sonar2 (no ramp up)	No response was observed.		174	0.25	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
mn12_179	Sonar1	There was a brief change in dive profile, but this lasted less than the duration of the exposure and did not rise to the level of a response.		173	0.33	2	0
mn12_179	Sonar2 (no ramp up)	There was a minor change in dive profile and a minor change in locomotion, with changes in direction and speed, but these did not last the duration of the exposure and did not rise to the level of a response.		176	0.11	3,3	0
mn12_180	Sonar1	The significant response included a moderate change in dive profile and moderate cessation of feeding that lasted longer than the duration of the exposure.	165		0.81	4,6	1
mn12_180	Sonar2 (no ramp up)	The significant response included moderate avoidance that lasted longer than the duration of the exposure.	127		0.98	6	1
Minke whale - 3S							

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
ba11_180	Sonar1	The significant response included prolonged avoidance that lasted greater than the duration of the exposure; this response might also have involved a cessation of feeding. There was also obvious aversion and sensitization, as shown by a further change in dive pattern and increase in travel speed away from the source during the avoidance.		138	<8	7	1
Bottlenose whale - 3S							
ha13_176	Sonar1	The significant response included an extended change in dive profile, with an unusually deep dive during the exposure, deeper than any dive recorded in this species. The response also included a prolonged avoidance and prolonged cessation of feeding, both of which which continued for > 7 hours, until the tag detached. In addition, a larger scale acoustic and visual survey of the larger exposed area showed that other animals in the area also evacuated for at least 6 hrs after the exposure.		122	<5	8	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Blue whales - BRS							
bw10_235a	MFAS	There was a decrease in body acceleration, but this was not outside normal behavior for this animal so did not rise to the level of a response.		165	1.1	3	0
bw10_235b	MFAS	No response was observed.		143	1.7	0	0
bw10_238a	MFAS	No response was observed.		143	4.5	0	0
bw10_239b	MFAS	There was a change in feeding behavior, a minor cessation of feeding, and an increase in speed but not avoidance, and none of these responses lasted the duration of the exposure so this did not rise to the level of a response for this analysis.		159	2.8	6/5	0
bw10_240a	MFAS	No response was observed.		163	0.5	0	0
bw10_240b	MFAS	No response was observed.		154	3.7	0	0
bw10_243a	PRN	No response was observed.		148	4.6	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 μPa)*	*Max RL Without a Response (dB re 1 μPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
bw10_243b	PRN	There was a general heading change before start of exposure, but no response to the exposure was observed.		153	0.8	0/2	0
bw10_244b	PRN	No response was observed.		160	1.2	0	0
bw10_244c	PRN	The significant response included a prolonged cessation of feeding which lasted longer than the duration of the exposure.	107		1.6	7	1
bw10_245a	PRN	No response was observed.		145	7.7	0	0
bw10_246a	MFAS	No response was observed.		159	1.5	0	0
bw10_246b	MFAS	No response was observed.		161	1.3	0	0
bw10_251a	PRN	There was a minor change in dive profile and MSA and a heading change, these did not last the duration of the exposure and did not rise to the level of a response.		154	0.9	3/7	0
bw10_265a	MFAS	No response was observed.		155	1.9	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
bw10_266a	MFAS	The significant response was cessation of feeding; this lasted longer than the duration of the exposure. Additional responses included an extended change in dive profile, and a moderate change in locomotion.	146		1.3	7	1
bw11_210a	MFAS	No response was observed.		161	1.2	0	0
bw11_210b	MFAS	The significant response included cessation of feeding, an increase in speed leading to avoidance, and a change in dive behavior; these lasted the duration of the exposure.	117		0.8	6/7	1
bw11_211a	PRN	No response was observed.		154	1.1	0	0
bw11_213b	MFAS	No response was observed.		160	1.0	0	0
bw11_214b	PRN	Researchers scored this as a moderate cessation of feeding, a decrease in lunges, a moderate change in orientation, and a slight increase in speed; these did not last the duration of the exposure and so did not rise to the level of a response for this analysis.		149	0.4	6	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
bw11_218a	PRN	There was a shallow dive but it started before exposure, the animal began feeding after and therefore there was no response.		130	5.6	0	0
bw11_218b	PRN	No response was observed.		161	1.2	0	0
bw11_219b	MFAS	There was a decrease in MSA, a change in heading, and a change in feeding behavior prior to start of exposure, during the exposure there was a change in dive behavior that did not last the duration of the exposure.		155	1.3	3/4	0
bw11_220b	MFAS	There was a moderate cessation of feeding, with a longer surface series, along with minor avoidance and a minor change in dive behavior; however, the animal returned to feeding during the exposure and therefore this did not rise to the level of a response for this analysis.		136	1.2	5/6	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 μPa)*	*Max RL Without a Response (dB re 1 μPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
bw11_221a	PRN	There was a minor/moderate cessation of foraging, but no clear avoidance, and the animal resumed foraging during the exposure so this did not rise to the level of a response for this analysis.		151	0.6	5	0
bw11_221b	PRN	There was a brief heading change and a minor orientation away from source, but this did not rise to the level of a response.		152	0.6	1	0
bw12_292a	PRN	No response was observed.		149	1.2	0	0
bw13_191a	Real MFAS	There was an increase in foraging behavior, no other response was observed.		146	19.5	0	0
bw13_259a	MFAS	No response was observed.		127	5.2	0	0
Beaked whales - BRS							

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
zc10_272a	MFAS	The significant response included moderate/prolonged cessation of clicking (indicative of foraging), moderate/ sustained avoidance and an increase in speed and body acceleration as well as a change in direction, these lasted longer than the duration of the exposure	98		3-5	6/7	1
bb12_214a	MFAS	There was an increase in speed, a change in heading, and possible moderate avoidance, and a change in depth/dive behavior at start of exposure, but the animal resumed foraging during the exposure therefore this did not rise to the level of a response.		138	3-5	4/6	0
zc11_267a	MFAS	The significant response was a prolonged cessation of feeding and sustained avoidance which lasted longer than the duration of the response. Additional responses included an unusual dive profile, and a decrease in speed/body acceleration.	95		3-5	6/7	1
zc13_210a	Real MFAS	No response was observed.		124	>60	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 μPa)*	*Max RL Without a Response (dB re 1 μPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
North Atlantic right whale - Alarm signal							
NARW_1	Alarm	Response included cessation of dive, rapid ascent, an abnormally long surface interval, and more time spent at subsurface depths.	148		Estimated: within one kilometer	5	1
NARW_2	Alarm	Response included cessation of dive, rapid ascent, an abnormally long surface interval, and more time spent at subsurface depths.	143		Estimated: within one kilometer	5	1
NARW_3	Alarm	Response included cessation of dive, rapid ascent, an abnormally long surface interval, and more time spent at subsurface depths.	137		Estimated: within one kilometer	5	1
NARW_4	Alarm	Response included cessation of dive, rapid ascent, an abnormally long surface interval, and more time spent at subsurface depths.	135		Estimated: within one kilometer	5	1
NARW_5	Alarm	Response included cessation of dive, rapid ascent, an abnormally long surface interval, and more time spent at subsurface depths.	133		Estimated: within one kilometer	5	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
NARW_6	Alarm	No response was observed.	134		Estimated: within one kilometer	0	0
Fin whales - SURTASS LFA							
Fin whale 1	LFAS	No response was observed.		148	NA	0	0
Fin whale 2	LFAS	No response was observed.		148	NA	0	0
Fin whale 3	LFAS	No response was observed.		148	NA	0	0
Fin whale 4	LFAS	No response was observed.		148	NA	0	0
Fin whale 5	LFAS	No response was observed.		148	NA	0	0
Blue whale - SURTASS LFA							
Blue whale 1	LFAS	No response was observed.		150	NA	0	0
Humpback whales - SURTASS LFA							
Singer 1	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	132		4.3	5	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 µPa)***	***Max RL Without a Response (dB re 1 µPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Singer 2	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	142		0.5	5	0
Singer 3	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	121		<11.3	5	0
Singer 4	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	126		<6.7	5	0
Singer 5	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	122		4.5	5	0
Singer 6	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.	138		0.5	5	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Singer 7	LFAS	The singer stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar.		124	5.2	0	0
Singer 8	LFAS	The singer stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar.		133	1	0	0
Singer 9	LFAS	The singer stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar.		137	1.2	0	0
Singer 10	LFAS	The singer stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar.		122	8.0	0	0
Singer 11	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		124	6.7	0	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 µPa)***	***Max RL Without a Response (dB re 1 µPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Singer 12	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		150	1.3	0	0
Singer 13	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		150	0.4	0	0
Singer 14	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		140	7.4	0	0
Singer 15	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		129	3.8	0	0
Singer 16	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		132	16.6	0	0
Singer 17	LFAS	The singer did not stop vocalizing during the sonar playback, therefore no response was observed.		133	7.3	0	0
Bottlenose dolphins - CES							
Dolphin 1	MFAS	No response.		115	0.01	0	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 μPa)*	*Max RL Without a Response (dB re 1 μPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Dolphin 2	MFAS	Minor change in respiration rate on one trial.	115		0.01	3	0
Dolphin 3	MFAS	Minor change in respiration rate on one trial.	115		0.01	3	0
Dolphin 4	MFAS	No response.		115	0.01	0	0
Dolphin 5	MFAS	No response.		115	0.01	0	0
Dolphin 6	MFAS	No response.		130	0.01	0	0
Dolphin 7	MFAS	Minor change in respiration rate on two trials.	130		0.01	3	0
Dolphin 8	MFAS	Significant response was refusal to participate on tenth trial. Minor change in respiration on one trial.	130		0.01	7	1
Dolphin 9	MFAS	Minor change in respiration rate on nine trials.	130		0.01	3	0
Dolphin 10	MFAS	No response.		130	0.01	0	0
Dolphin 11	MFAS	Minor change in respiration rate on one trial.	145		0.01	3	0

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 μPa)*	*Max RL Without a Response (dB re 1 μPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Dolphin 12	MFAS	Significant response was fluke slaps on two trials.	145		0.01	6	1
Dolphin 13	MFAS	Significant response was refusal to participate on tenth trial.	145		0.01	7	1
Dolphin 14	MFAS	No response.		145	0.01	0	0
Dolphin 15	MFAS	Minor change in respiration rate on two trials.	145		0.01	3	0
Dolphin 16	MFAS	Minor change in respiration rate on one trial.	160		0.01	3	0
Dolphin 17	MFAS	Minor change in respiration rate on one trial.	160		0.01	3	0
Dolphin 18	MFAS	No response.		160	0.01	0	0
Dolphin 19	MFAS	Significant response was refusal to participate on first trial.	160		0.01	7	1
Dolphin 20	MFAS	Minor change in respiration rate on one trial.	160		0.01	3	0
Dolphin 21	MFAS	Minor change in respiration rate on one trial.	175		0.01	3	0

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Dolphin 22	MFAS	Significant response was refusal to participate on three trials and fluke slaps on six trials. Minor changes in respiration.	175		0.01	7	1
Dolphin 23	MFAS	Significant response was refusal to participate on all trials.	175		0.01	7	1
Dolphin 24	MFAS	Significant response was refusal to participate on seven trials. Minor change in respiration on nine trials.	175		0.01	7	1
Dolphin 25	MFAS	Minor change in respiration rate on one trial.	175		0.01	3	0
Dolphin 26	MFAS	Significant response was refusal to participate all trials.	185		0.01	7	1
Dolphin 27	MFAS	Significant response was refusal to participate all trials.	185		0.01	7	1
Dolphin 28	MFAS	Significant response was refusal to participate all trials.	185		0.01	7	1
Dolphin 29	MFAS	Significant response was refusal to participate all trials.	185		0.01	7	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Dolphin 30	MFAS	Significant response was refusal to participate all trials.	185		0.01	7	1
California sea lions - CES							
Sea Lion 1	MFAS	Significant response was refusal to participate on four trials. Minor changes in duration of submergence and respiration rate throughout trials.	125		0.01	7	1
Sea Lion 2	MFAS	Minor change in respiration on three trials.	125		0.01	3	0
Sea Lion 3	MFAS	Minor change in respiration on three trials.	125		0.01	3	0
Sea Lion 4	MFAS	Significant response was refusal to participate on two trials.	140		0.01	7	1
Sea Lion 5	MFAS	No response.		140	0.01	0	0
Sea Lion 6	MFAS	No response.		140	0.01	0	0
Sea Lion 7	MFAS	Significant response was to haul out on five trials and refusal to participate on remaining five trials.	155		0.01	9	1

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 µPa)***	***Max RL Without a Response (dB re 1 µPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Sea Lion 8	MFAS	Minor change in respiration rate on four trials.	155		0.01	3	0
Sea Lion 9	MFAS	Minor change in respiration rate on three trials.	155		0.01	3	0
Sea Lion 10	MFAS	Significant response was to haul out on eight trials and refusal to participate on remaining two trials.	170		0.01	9	1
Sea Lion 11	MFAS	Significant response was refusal to participate on seven trials. Minor change in respiration rate on nine trials. Increase in submergence time throughout.	170		0.01	7	1
Sea Lion 12	MFAS	Significant response was to haul out on one trial and refuse to participate on remaining eight trials. Minor change in respiration rate on nine trials.	170		0.01	9	1
Sea Lion 13	MFAS	Significant response was to haul out on five trials and refusal to participate on five trials.	185		0.01	9	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Sea Lion 14	MFAS	Significant response was refusal to participate on all trials.	185		0.01	7	1
Sea Lion 15	MFAS	Significant response was refusal to participate on two trials. Minor increase in respiration rate on two trials.	185		0.01	7	1
Gray seals - CES							
Gray Seal 1	MFAS	Significant response was a flight response and abandonment of feeding, and animal sensitized to the sound.	170		0.001	6	1
Gray Seal 2	MFAS	Significant response was a flight response and abandonment of feeding, and animal sensitized to the sound.	170		0.001	6	1
Gray Seal 3	MFAS	Significant response was a flight response and abandonment of feeding, and animal sensitized to the sound.	170		0.001	6	1

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 µPa)***	***Max RL Without a Response (dB re 1 µPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Gray Seal 4	MFAS	Significant response was a flight response and abandonment of feeding, and animal sensitized to the sound.	170		0.001	6	1
Gray Seal 5	MFAS	Significant response was a flight response and abandonment of feeding, and animal sensitized to the sound.	170		0.001	6	1
Gray Seal 6	MFAS	No response occurred, and animal habituated to the sound.		170	0.001	0	0
Gray Seal 7	MFAS	No response occurred, and animal habituated to the sound.		170	0.001	0	0
Gray Seal 1	MFAS	Significant response was a flight response and abandonment of feeding.	160		0.001	6	1
Gray Seal 2	MFAS	Significant response was a flight response and abandonment of feeding.	155		0.001	6	1
Gray Seal 3	MFAS	Significant response was a flight response and abandonment of feeding.	160		0.001	6	1

Animal	***Exposure***	***Description of Response***	***RL at Response (dB re 1 μPa)***	***Max RL Without a Response (dB re 1 μPa)***	***Distance at Response or CPA for No Response (km)***	***Southall Severity***	***Significant Behavioral Response***
Gray Seal 4	MFAS	Significant response was a flight response and abandonment of feeding.	160		0.001	6	1
Gray Seal 5	MFAS	Significant response was a flight response and abandonment of feeding.	159		0.001	6	1
Gray Seal 6	MFAS	No response occurred.		180	0.001	0	0
Gray Seal 7	MFAS	No response occurred.		180	0.001	0	0
Hooded seals - CES							
Hooded seal 1	MFAS	Significant response was active avoidance of sound source, reduced dive activity, and floating with head out of water.	165		NA	6	1
Hooded seal 2	MFAS	Significant response was active avoidance of sound source, reduced dive activity, and floating with head out of water.	167		NA	6	1

Animal	*Exposure*	*Description of Response*	*RL at Response (dB re 1 µPa)*	*Max RL Without a Response (dB re 1 µPa)*	*Distance at Response or CPA for No Response (km)*	*Southall Severity*	*Significant Behavioral Response*
Hooded seal 3	MFAS	Significant response was active avoidance of sound source, reduced dive activity, and floating with head out of water.	169		NA	6	1
Hooded seal 4	MFAS	Significant response was active avoidance of sound source, reduced dive activity, and floating with head out of water.	170		NA	6	1

APPENDIX C. PHASE III SUMMARY OF CRITERIA FOR DETERMINING ACOUSTIC AND EXPLOSIVE EFFECTS TO MARINE SPECIES FROM NAVY SOUND SOURCES

C.1. Introduction

The following is a brief summary of the Navy's proposed Phase III Physiological and Behavioral Criteria and Thresholds for predicting acoustic and explosive effects to marine species. It is primarily meant to guide the NAEMO analysts in order to begin the Phase III acoustic and explosive modeling.

C.2. General

The highest order effect predicted is the one that is reported: mortality > non-auditory injury > PTS > TTS > behavioral response.

Sound exposure levels (SEL) and root-mean-square (rms) sound pressure levels (SPL) will be calculated based on the actual signal duration. For impulsive sounds, SEL at the receiver shall be calculated based on 90% of the weighted received energy over the duration of an individual pulse. (Note that this differs from Phase II SEL calculation for explosives, which consisted of calculating SEL using the rms received level over an assumed one-second duration rather than the actual pulse duration.)

C.3. Marine Species Hearing Groups

Table C.1. Species group designations for Navy Phase III auditory weighting functions.

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

C.4. Auditory Weighting Functions and Temporary & PTS For all Analyzed Navy Sound Sources

In Phase III, auditory weighting functions will be used to adjust the received SEL before comparing that level to thresholds for TTS and PTS for both impulsive and non-impulsive sounds (See Table C.2 and Figure C.1). Auditory weighting functions will not be applied when calculating SPL in any instance. TTS and PTS use the weighted SEL for both non-impulsive and impulsive sound types.

For sonar and other transducers, pings and active transmissions are summed to a cumulative SEL (cSEL) during an event or over 24 hours for multiday events. The cSEL is then weighted using the appropriate weighting function for that hearing group, before being compared to the threshold for determining TTS or PTS (See Figure C.2). Similarly, for broadband sources (i.e., explosives, airguns, impact pile driving, and vibratory pile driving), cumulative SEL is summed across the full frequency range and then weighted using the appropriate weighting function for that hearing group before being compared to the threshold for determining TTS or PTS (See Figure C.3).

Although frequency weighting is applied, upper and lower frequency cutoffs will be considered as to what sources and events should be assessed for a hearing group.

Table C.2. Summary of Navy Phase III weighting function parameters and TTS/PTS thresholds at that hearing group's most sensitive frequency. SEL thresholds in dB re 1 µPa²s underwater and dB re (20 µPa)²s in air. Peak SPL thresholds in dB re 1 µPa underwater and dB re 20 µPa in air (groups OA and PA only).

$W(f)=C+10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$						***Non-impulsive***		***Impulse***			
						TTS threshold	***PTS threshold***	***TTS threshold***		***PTS threshold***	
Group	***a***	***b***	***f_1 (kHz)***	***f_2 (kHz)***	***C (dB)***	***SEL (weighted)***	***SEL (weighted)***	***SEL (weighted)***	***peak SPL (unweighted)***	***SEL (weighted)***	***peak SPL (unweighted)***
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218
TU	1.4	2	0.077	0.44	2.35	200	220	189	226	204	232
OA	1.4	2	2.0	20	1.39	157	177	146	170	161	176
PA	2	2	0.75	8.3	1.50	134	154	123	155	138	161

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

The most significant differences between the Phase II and Phase III functions include the following:

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

(2) The sea turtle thresholds are higher at all frequencies compared to those used in Phase II. In Phase II, turtles were assumed to have TTS thresholds at their most susceptible frequency equal to those of MF cetaceans at their most susceptible frequency. However, sea turtles have best sensitivity at lower frequencies than MF cetaceans. Turtles are known to have poor auditory sensitivity (Bartol & Ketten, 2006; Dow Piniak et al., 2012; Martin et al., 2012) and TTS thresholds for turtles are likely more similar to those of fishes than to marine mammals (Popper et al., 2014). Therefore, the TTS/PTS thresholds for turtles were increased relative to those used in Phase II.

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

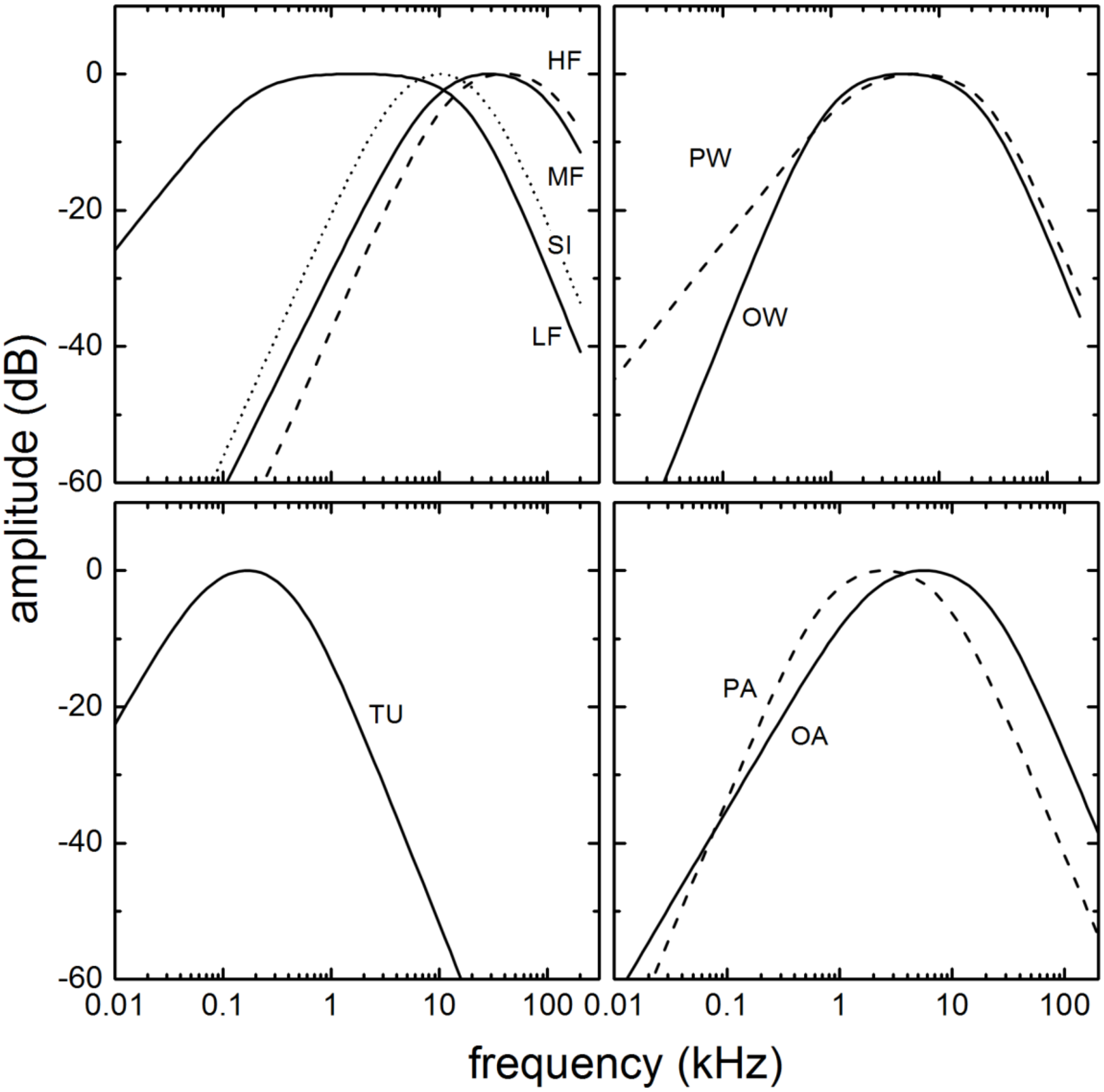

Figure C.1. Navy Phase III weighting functions for all species groups. Parameters required to generate the functions are provided in Table C.2 above.

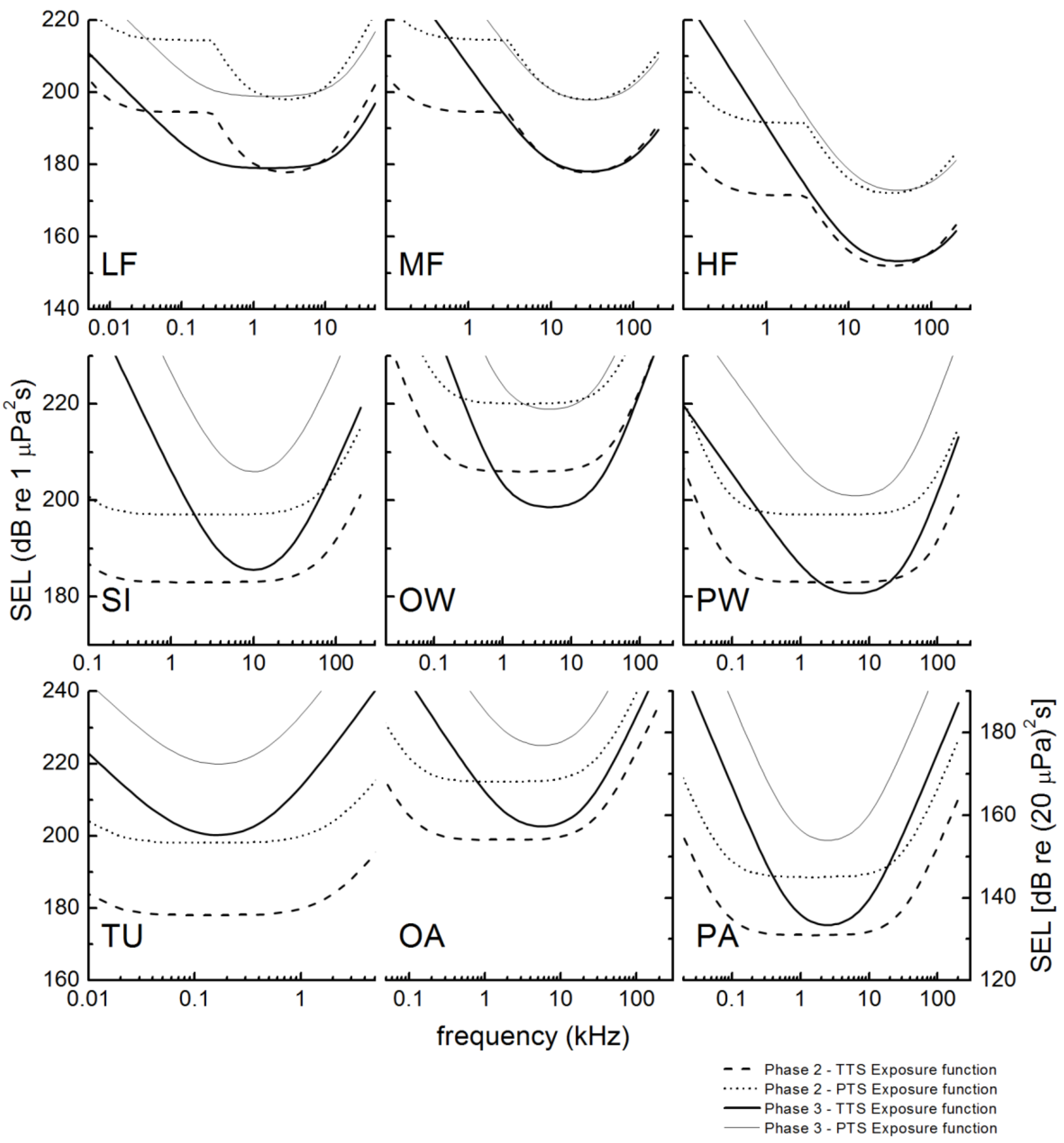

Figure C.2. TTS and PTS exposure functions for sonar and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase III TTS exposure functions (Table C.2). Light gray solid lines — Navy Phase III PTS exposure functions (Table C.2). Dashed lines — Navy Phase II TTS exposure functions. Short dashed lines — Navy Phase II PTS exposure functions.

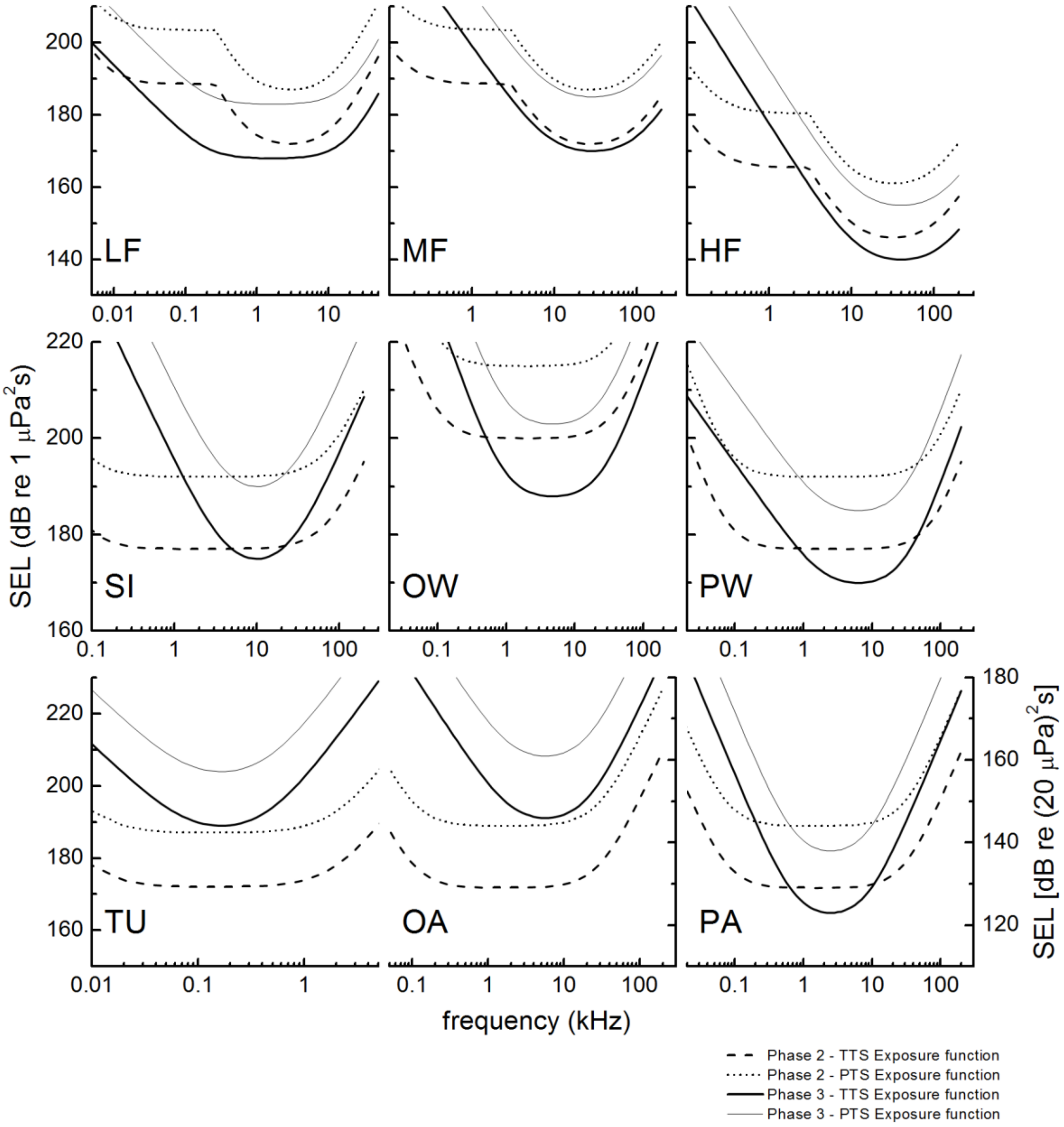

Figure C.3. TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase III TTS exposure functions (Table C.2). Light gray solid lines — Navy Phase III PTS exposure functions (Table C.2). Dashed lines — Navy Phase II TTS exposure functions. Short dashed lines — Navy Phase II PTS exposure functions.

C.5. Behavioral Response for Sonar & Other Transducers

The Phase III behavioral criteria will be defined for specific groups based on recent behavioral data. The Behavioral Response Functions (BRFs) are used to estimate the percentage of an exposed population likely to exhibit a significant behavioral response at a given received SPL. The 120 dB re 1 µPa step function will continue to be used for harbor porpoises. All functions will be used in conjunction with a distance cut-off (see below).

The biphasic dose-response function:

$$P(L_R) = [\frac{p}{1+10^{(L_1-L_R)h_1}}] + [\frac{1-p}{1+10^{(L_2-L_R)h_2}}] \qquad \text{(C.1)}$$

The BRFs use unweighted SPL ($\text{rms}_{90\%}$) for sonar and other transducers (see Table C.3, Figure C.4, Figure C.5, Figure C.6, and Figure C.7).

Upper and lower frequency cutoffs will be considered when assessing potential acoustic impacts. Sources with most of their energy within a functional hearing group's frequency cutoffs will be assessed for potential behavioral responses within NAEMO.

Sound propagation for sonar and other active acoustic sources should be modeled to a 100 dB re 1 µPa received level or 100 km, whichever is closer to the source. Below 100 dB re 1 µPa no responses will be calculated because the risk of a significant behavioral response is assumed to be negligible.

Table C.3. BRF biphasic dose response function equation values, and overall maximum and 50% probability received SPLs. SPLs are given in dB re 1 µPa (rms). $P(L_R)$ is the probability of response, L_R is the received SPL, p is the proportion of the curve comprising the second (stronger) phase, L_1 is the SPL at the midpoint proportion of the first phase, L_2 is the SPL at the midpoint proportion of the second phase, and h_1 and h_2 are the hill slopes of the two phases. Also, step function for harbor porpoises.

Biphasic Dose Response Function: $P(L_R) = [\frac{p}{1+10^{(L_1-L_R)h_1}}] + [\frac{1-p}{1+10^{(L_2-L_R)h_2}}]$							
Criteria Group	***Max RL***	***50% RL***	***L_1***	***L_2***	***h_1***	***h_2***	***p***
Odontocetes	185	157	118	161	0.07	0.08	0.23
Pinnipeds	185	166	110	168	0.09	.10	0.15
Mysticetes (and Manatees)	185	177	136	178	0.07	0.13	0.18
Beaked Whales	185	144	98	145	0.16	0.07	0.11
Harbor porpoises	step function of 120 dB re 1 µPa						

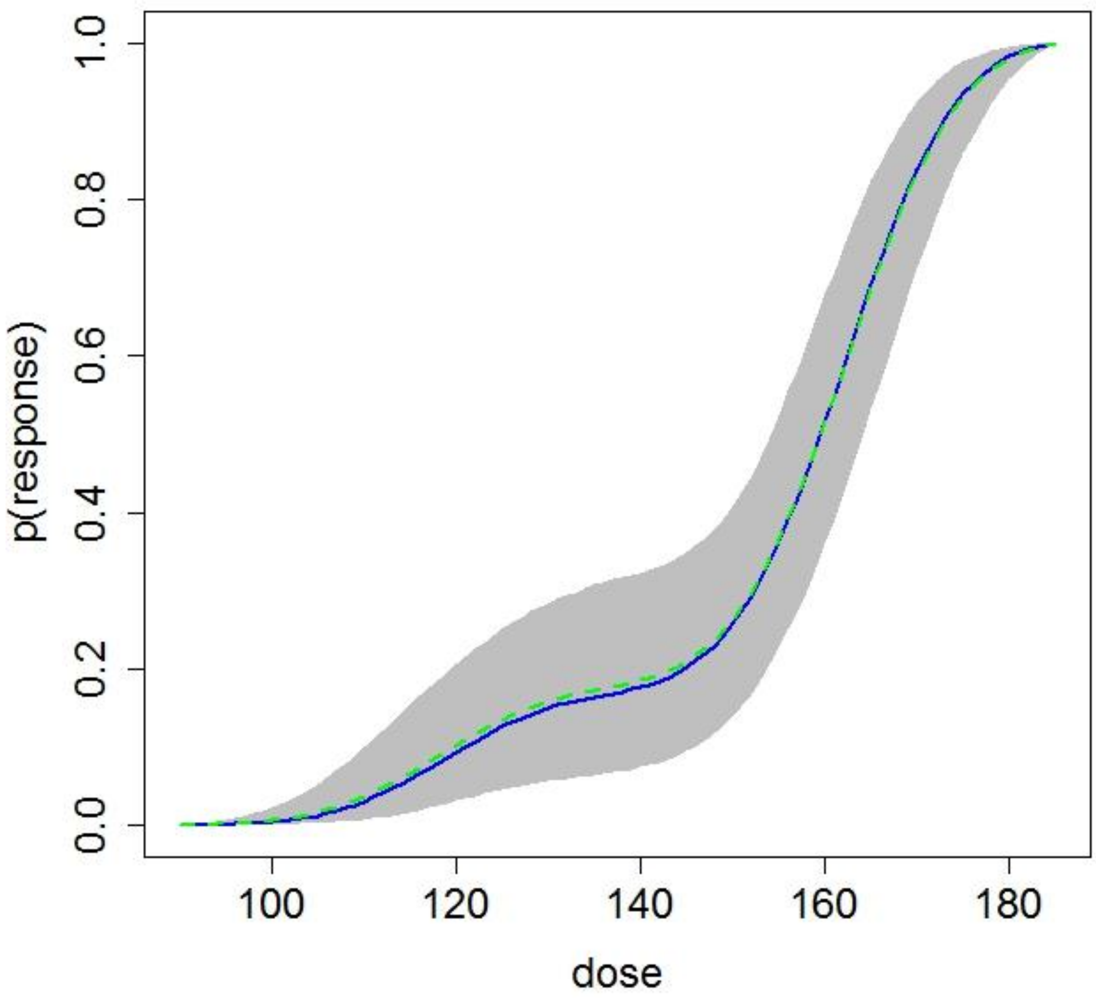

Figure C.4. The Bayesian biphasic dose-response BRF for Odontocetes. This curve has a 50% probability of response at 157 dB re 1 µPa. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

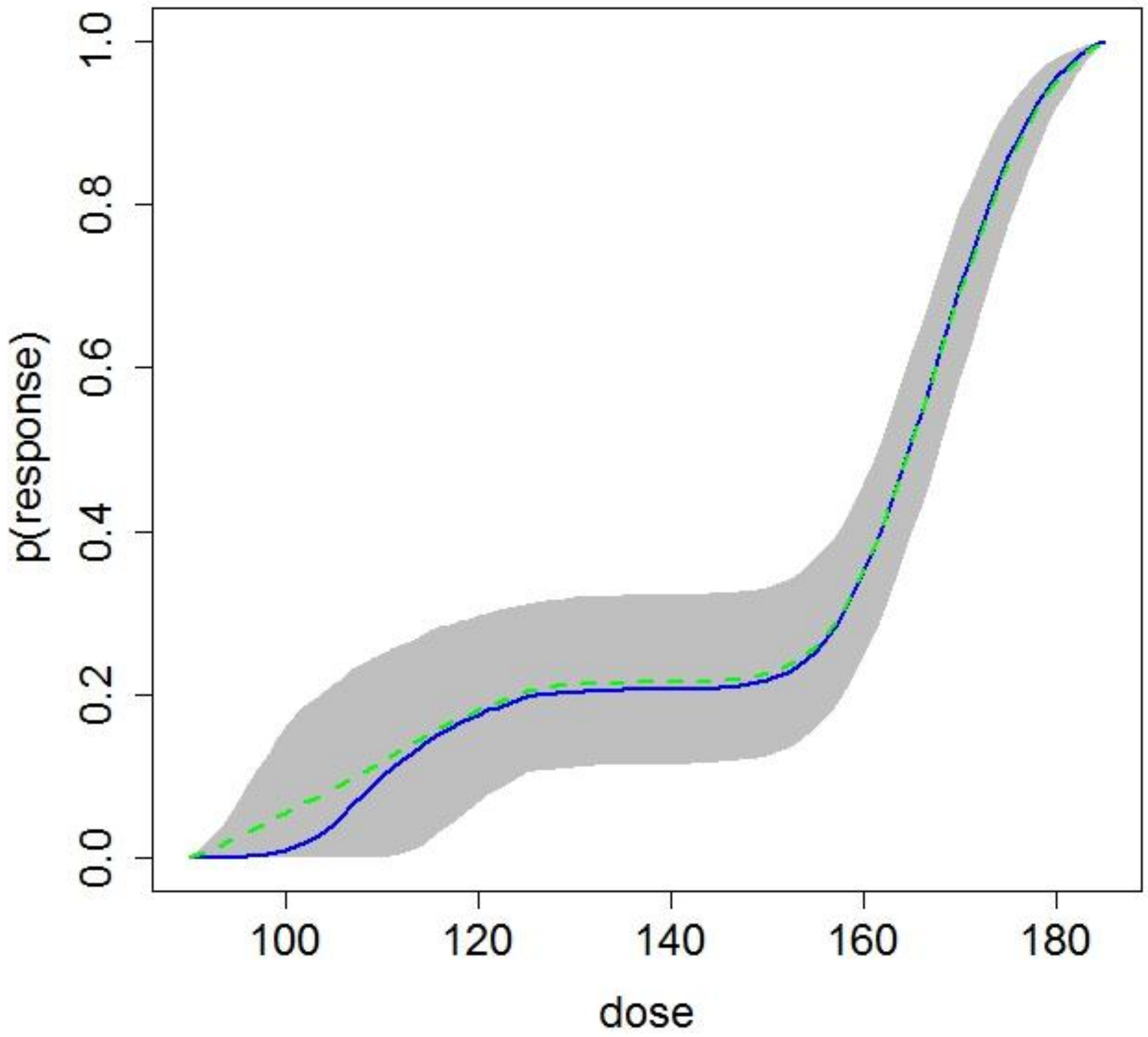

Figure C.5. The Bayesian biphasic dose-response BRF for Pinnipeds. This curve has a 50% probability of response at 166 dB re 1 µPa. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

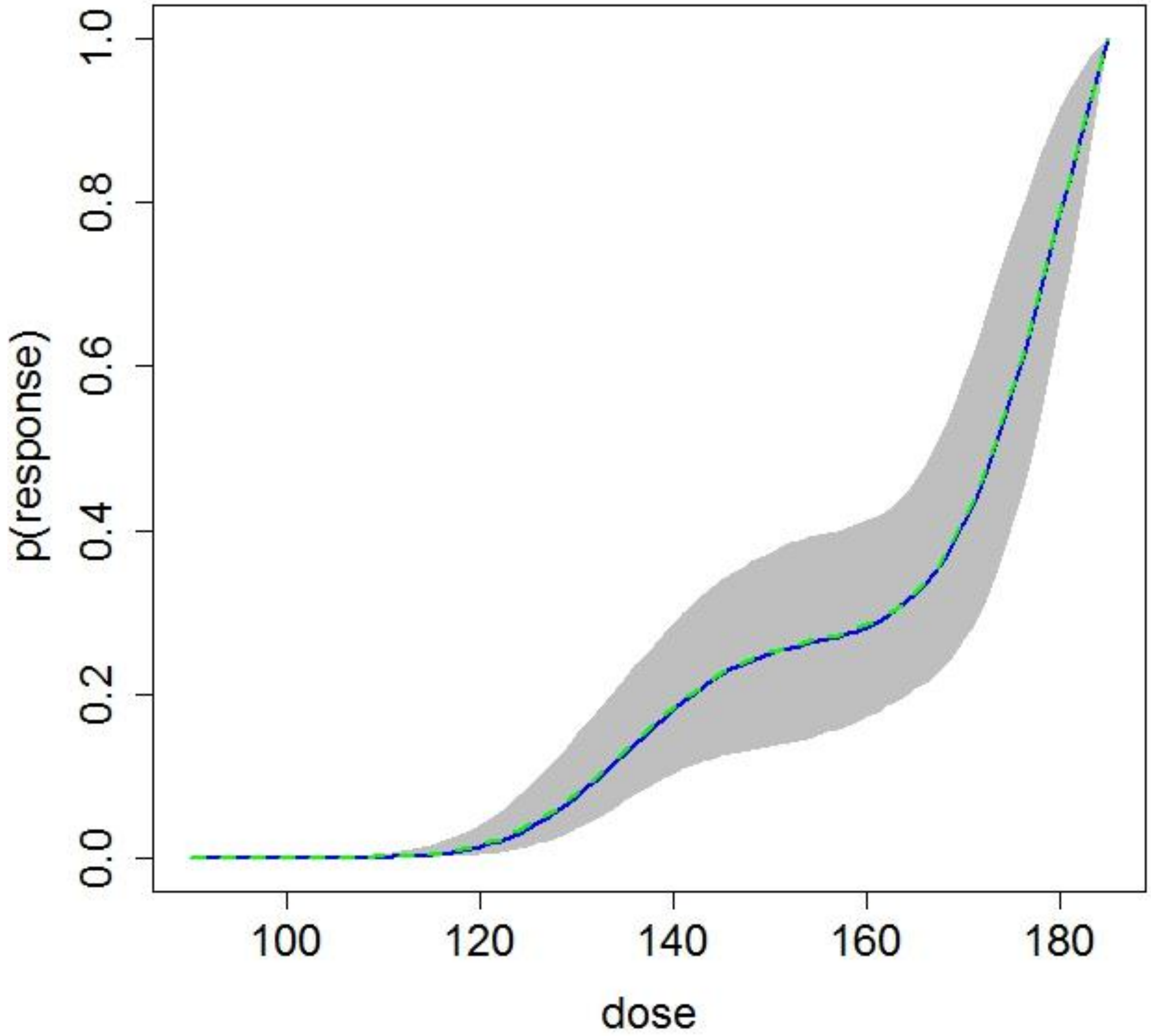

Figure C.6. The Bayesian biphasic dose-response BRF for Mysticetes. This curve has a 50% probability of response at 177 dB re 1 µPa. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

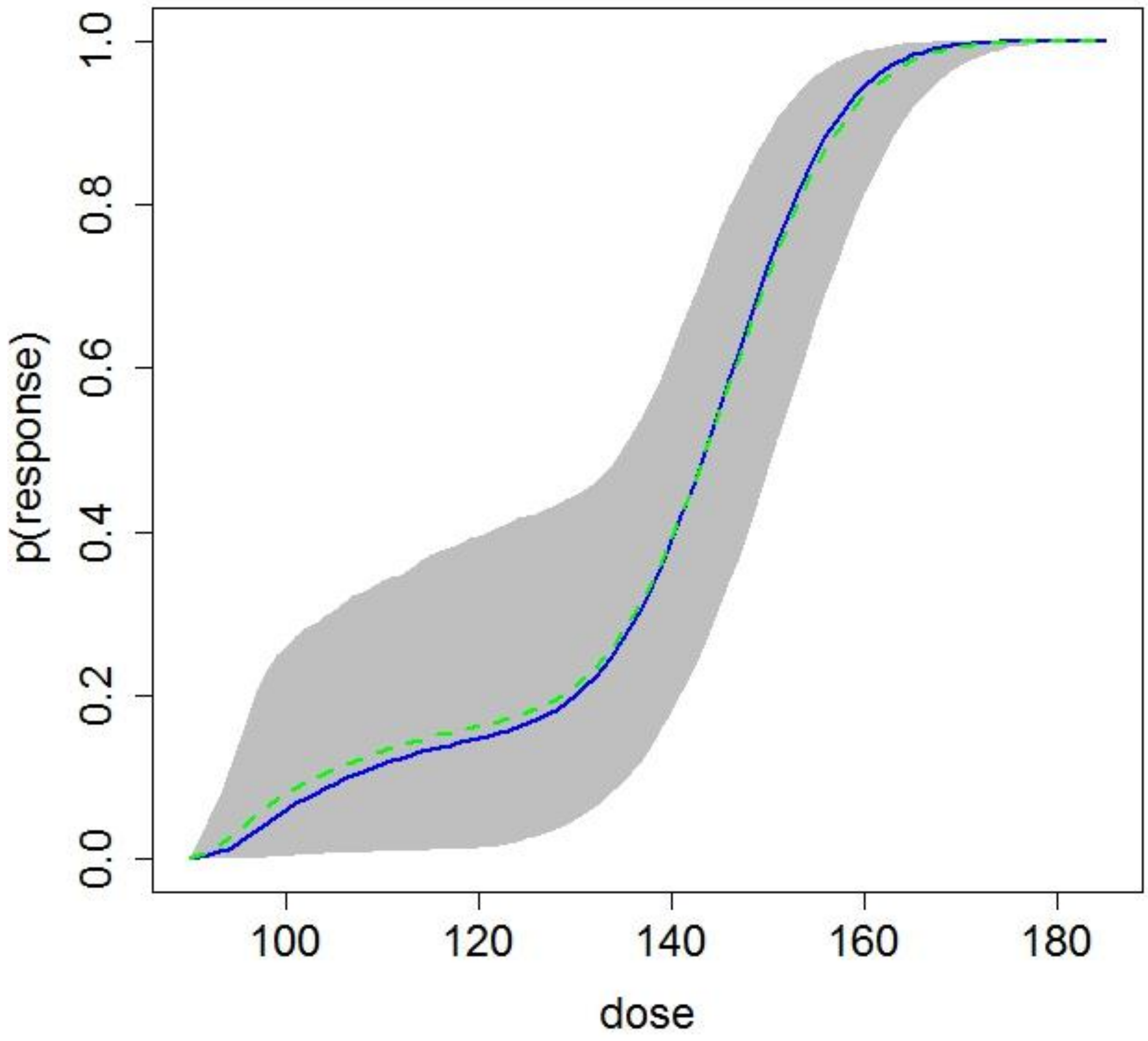

Figure C.7. The Bayesian biphasic dose-response BRF for Beaked Whales. This curve has a 50% probability of response at 144 dB re 1 µPa. The blue solid line represents the Bayesian Posterior median values, the green dashed line represents the biphasic fit, and the gray represents the variance. [X-Axis: Received Level (dB re 1 µPa), Y-Axis: Probability of Response]

Distance cut-offs will be designated for species group, beyond which the criteria for that group will not apply (see Table C.4).

Table C.4. Cutoff distances for (a) moderate source level, single sound source platform training and testing events and for (b) all other events with multiple sound source platforms or sonar with source levels at or exceeding 215 dB re 1 µPa @ 1 m.

		Cutoff Distances	
Criteria Group		***Moderate SL / Single Platform***	***High SL / Multi-Platform***
Low-Frequency Cetaceans (Mysticetes)	LF	10 km	20 km
Mid-Frequency Cetaceans	MF	10 km	20 km
	Beaked Whales	25 km	50 km
High-Frequency Cetaceans	HF	10 km	20 km
	Harbor porpoises	20 km	40 km
Sirenians	SI	10 km	20 km
Phocid Pinnipeds (In-Water)	PW	5 km	10 km
Otariid Pinnipeds, Walruses, Sea Otters, Polar Bears (In-Water)	OW	5 km	10 km

Sea turtle behavioral criteria for sonar and other transducers was developed with NMFS based on exposure to air guns (McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to sonar and other transducers.

Per discussions with NMFS, the received sound level at which sea turtles are expected to actively avoid air gun exposures, *175 dB re 1 µPa SPL rms* based on studies of sea turtles exposed to air guns (McCauley et al., 2000), is also expected to be the received sound level at which sea turtles would actively avoid exposure to sonar and other transducers during Navy training and testing activities. This behavioral threshold will be applied to sources up to 2 kHz.

The working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide a parametric description that sea turtles would have a low behavioral response to low-frequency sonar and other transducers at near (tens of meters), intermediate (hundreds of meters), and far (thousands of meters) distances. A response would likely decrease over increasing distance.

C.6. Behavioral Response for Multiple Impulses from Explosives

Phase III explosive criteria for marine mammals will be the hearing groups TTS threshold minus 5 dB (see Table C.5) for events that contain multiple impulses from explosives underwater. Note, this is the same approach taken in Phase II explosive analysis.

Table C.5. Phase III behavioral thresholds for explosives for marine mammals. The received signal is weighted using the appropriate weighting functions (shown above in Figure C.2 for Phase III functions) before comparing to the numerical thresholds listed in this table. Weighted SEL thresholds in dB re 1 µPa^{2}s underwater, and unweighted SEL thresholds in-air is dB re 20 µPa^{2}s.

Medium	***Group***	***SEL***
Underwater	LF	163 (WF_{LF})
Underwater	MF	165 (WF_{MF})
Underwater	HF	135 (WF_{HF})
Underwater	SI	170 (WF_{SI})
Underwater	OW	183 (WF_{OW})
Underwater	PW	165 (WF_{PW})
In-Air	OA	100 dB re 20 µPa^{2}s (Unweighted)
In-Air	PA	100 dB re 20 µPa^{2}s (Unweighted)

Sea turtle behavioral criteria for explosives was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to explosives.

Per discussions with NMFS, the received sound level at which sea turtles are expected to actively avoid air gun exposures, *175 dB re 1 µPa SPL rms* based on studies of sea turtles exposed to air guns (McCauley et al., 2000), is also expected to be the received sound level at which sea turtles would actively avoid events with multiple explosions during Navy training and testing activities.

C.7. Behavioral Criteria for Pile Driving and Air guns for Marine Mammals and Sea Turtles

Thresholds for TTS and PTS for impact pile driving and air guns will be the same impulsive thresholds discussed above for marine mammals (see Table C.2). Vibratory pile extraction will use the non-impulsive PTS and TTS thresholds for marine mammals (see Table C.2).

Determination of a significant behavioral response for marine mammals will be based on SPL of the highest received signal (see Table C.6).

Table C.6. Pile Driving and Air gun Behavioral Thresholds for marine mammals to be used in Phase III Analysis.

Source	***Behavioral Threshold (SPL in dB re 1 μPa [rms$_{90\%}$])***
Vibratory Pile Extraction	120 dB
Impact Pile Driving and Airgun	160 dB

Sea turtle behavioral criteria for air guns, and impact and vibratory pile driving was developed with NMFS based on exposure to air guns (See McCauley et al., 2000). In addition, the working group that prepared the ANSI Sound Exposure Guidelines (Popper et al., 2014) provide parametric descriptors of sea turtle behavioral responses to air guns and pile driving.

Per discussions with NMFS, a threshold of *175 dB re 1 μPa SPL rms* is applied to estimate sea turtle behavioral reactions to repeated air gun firing during Navy testing activities. Additionally, the received sound level at which sea turtles are expected to actively avoid air gun exposures, *175 dB re 1 μPa SPL rms* (See McCauley et al., 2000), is expected to be the received sound level at which sea turtles would actively avoid exposure to impact and vibratory pile driving noise during Navy training activities.

C.8. Mortality and Injury (Non-Auditory) for Explosives

The criterion for mortality is based on severe lung injury (derived from Goertner, 1982) and the criteria for non-auditory injury are based on slight lung injury or gastrointestinal (GI) tract injury.

Mortality and slight lung injury impacts on marine mammals and sea turtles will be predicted using thresholds for both calf/pup/juvenile and adult weights (Table C.9). The 50% thresholds for mortality and slight lung injury will be used to calculate impacts. The onset (i.e., 1%) thresholds will be used to model zones of impact to inform mitigation assessment. At this time, it is undetermined if the 50% threshold will be accepted for use in quantifying impacts. Therefore, up to four sets of predictions will result for each species:

1. mortality and slight lung injury for calf/pup/juvenile mass using 50% response thresholds
2. mortality and slight lung injury for median adult mass using 50% response thresholds
3. mortality and slight lung injury for calf/pup/juvenile mass using onset thresholds

4. mortality and slight lung injury for median adult mass using onset thresholds

Adult and calf impacts will be apportioned during post-processing dependent on area and season.

Impulse integration time will be the lesser of initial positive impulse or 20% lung resonance period (as described in Goertner, 1982). This assures that the received impulse is not over-predicted for signals that lack the rapid rise time capable of causing injuries.

An additional criterion for non-auditory injury is onset of GI tract injury, which is the same for all species for explosive impacts. To reasonably estimate the number of animals that could be injured due to exposure to high peak pressures, the Navy Phase III explosive analysis will use peak pressure injury threshold of 200 psi (243 dB re 1 µPa peak). To account for injuries seen at some lower level exposures, a peak pressure threshold of 104 psi (237 dB re 1 µPa peak) is proposed to estimate potential ranges to effect for the purposes of deriving appropriate mitigation ranges.

Two sets of thresholds are provided for use in non-auditory injury assessment. The first set provides thresholds to be used to estimate the number of animals that may be affected (see Table C.7). The second set provides thresholds to estimate farthest range for potential occurrence of an effect (see Table C.8).

Table C.7. Criteria to Quantitatively Assess Non-Auditory Injury due to Underwater Explosions.

Impact Assessment Criterion	*Threshold*
Mortality - Impulse	$144M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury - Impulse	$65.8M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury - Peak Pressure	243 dB re 1 µPa peak

Where M is animal mass (kg) and D is animal depth (m).

Table C.8. Onset of Effect Threshold for Estimating Ranges to Potential Effect.

Onset effect for mitigation consideration	*Threshold*
Onset Mortality - Impulse	$103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury - Impulse (Non-auditory)	$47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury - Peak Pressure (Non-auditory)	237 dB re 1 µPa peak

Where M is animal mass (kg) and D is animal depth (m).

Table C.9. Animal masses for analysis of impulse-based injury.

Species Name	Common Name	Calf / Pup Mass (kg)[1]	Adult Mass - Maximum [Typical Range][2]	Representative Adult Mass (kg)[2]
Cetaceans				
Family Balaenidae				
Eubalaena glacialis	North Atlantic right whale	910[a]	90,000[a]	18,000[z]
Eubalaena japonica	North Pacific right whale	910[a]	90,000[a]	18,000[z]
Family Balaenopteridae				
Balaenoptera acutorostrata	Minke whale	200[e]	13,500[d] [4,000 – 13,500[d]]	4,000
Balaenoptera borealis	Sei whale	650[f]	45,000[a] [20,000 – 25,000[d]]	20,000
Balaenoptera edeni	Bryde's whale	680[a]	40,000[a] [16,000 – 25,000[d]]	16,000
Balaenoptera musculus	Blue whale	2,000[d]	200,000[d] [72,000 – 135,000[b]]	72,000
Balaenoptera physalus	Fin whale	1,750[d]	120,000[a] [30,000 - 90,000[d]]	30,000
Megaptera novaeangliae	Humpback whale	680[a]	48,000[d] [25,000- 48,000[d]]	25,000
Family Eschrisctiidae				
Eschrichtius robustus	Gray whale	500[d]	45,000[b] [14,000-35,000[d]]	14,000
Family Delphinidae				
Delphinus capensis	Long-beaked common dolphin	9 (surrogate: short-beaked common dolphin)	235[b]	70 (surrogate: short-beaked common dolphin)
Delphinus delphis	Short-beaked common dolphin	9[g]	200[b] [70-173[d]]	70
Feresa attenuata	Pygmy killer whale	7 (surrogate: striped dolphin)	225[b] [150 – 225[d]]	150
Globicephala macrorhynchus	Short-finned pilot whale	37[a]	3950[d] [600 – 3950[d]]	600
Globicephala melas	Long-finned pilot whale	70[d]	2300 (M)[a], 1300 (F)[a] [280 – 1750[d]]	280
Grampus griseus	Risso's dolphin	47[h]	500[b]	150
Lagenodelphis hosei	Fraser's dolphin	19[a]	210 (M)[a], 160 (F)[a]	80
Lagenorhynchus acutus	Atlantic white-sided dolphin	20[a]	>230 (M)[a], >180 (F)[a]	90
Lagenorhynchus albirostris	White-beaked dolphin	40[d]	350 (M)[a], 310 (F)[a]	155
Lagenorhynchus obliquidens	Pacific white-sided dolphin	12[i]	200 (M)[a], 150 (F)[a] [75-181[d]]	75
Lissodelphis borealis	Northern right whale dolphin	7 (surrogate: striped dolphin)	115[b]	35
Orcinus orca	Killer whale	160[a]	10,500 (M)[d], >3800 (F)[a] [2,600 – 10,500[d]]	2,600

Species Name	Common Name	Calf / Pup Mass (kg)[1]	Adult Mass - Maximum [Typical Range][2]	Representative Adult Mass (kg)[2]
Peponocephala electra	Melon-headed whale	15[a]	275[b] [160 – 275[d]]	160
Pseudorca crassidens	False killer whale	80[e]	2200[d] [700 – 2,200[d]]	700
Stenella attenuata	Pantropical spotted dolphin	7 (surrogate: striped dolphin)	120 (M)[a] [100-119[d]]	36
Stenella clymene	Clymene dolphin	7 (surrogate: striped dolphin)	80 (M)[a], 75 (F)[a]	37
Stenella coeruleoalba	Striped dolphin	7[a]	160 (M)[a], 150 (F)[a]	75
Stenella frontalis	Atlantic spotted dolphin	7 (surrogate: striped dolphin)	143 (M)[d], 130 (F)[a]	65
Stenella longirostris	Spinner dolphin	7 (surrogate: striped dolphin)	78 (M)[a], 65 (F)[a]	32
Steno bredanensis	Rough-toothed dolphin	7 (surrogate: striped dolphin)	160 (M)[a] [122[d]]	48
Tursiops aduncus	Indo-Pacific bottlenose dolphin	9[a]	230 (M)[a], 180 (F)[a]	90
Tursiops truncates	Common bottlenose dolphin	14[a]	650 (M)[d], 260 (F)[a]	130
Family Kogiidae				
Kogia breviceps	Pygmy sperm whale	23[a]	450[b] [<400[d]]	135
Kogia sima	Dwarf sperm whale	14[j]	303[d] [210 – 303[d]]	91
Family Monodontidae				
Delphinapterus leucas	Beluga whale	80[d]	1100-1600 (M)[a], 700-1200 (F)[a] [400-1500[d]]	400
Monodon monoceros	Narwhal	80[a]	1600 (M)[a], 1000 (F)[a]	500
Family Phocoenidae				
Phocoenoides dalli	Dall's Porpoise	6[k]	170-200 (M)[a], 180 (F)[a] [123 – 200[d]]	90
Phocoena phocoena	Harbor porpoise	5[d]	90 (M)[d], 76 (F)[a] [40 – 90[d]]	40
Family Physeteridae				
Physeter macrocephalus	Sperm whale	1000[d]	57,000 (M)[a], 24,000 (F)[a] [16,000 – 57,000[d]]	16,000
Family Ziphiidae				
Berardius arnouxii	Arnoux's beaked whale	250 (surrogate: Cuvier's beaked whale)		3600 (surrogate: Baird's beaked whale)
Berardius berardii	Baird's beaked whale	250 (surrogate: Cuvier's beaked whale)	12,000[b]	3600
Hyperoodon ampullatus	Northern bottlenose whale	250 (surrogate: Cuvier's beaked whale)	2800-7500[a]	2250
Indopacetus pacificus	Longman's beaked whale	228[l]		510 (surrogate: True's beaked whale)
Mesoplodon bidens	Sowerby's beaked whale	170[a]	1300[b]	390

Species Name	**Common Name**	**Calf / Pup Mass (kg)[1]**	**Adult Mass - Maximum [Typical Range][2]**	**Representative Adult Mass (kg)[2]**
Mesoplodon carlhubbsi	Hubb's beaked whale	170 (surrogate: Sowerby's beaked whale)	1500[a]	450
Mesoplodon densirostris	Blainville's beaked whale	60[d]	>800 (M)[a], >1000 (F)[a]	400
Mesoplodon europaeus	Gervais' beaked whale	49[d]	>1200[a]	366
Mesoplodon ginkgodens	Ginkgo-toothed beaked whale	60 (surrogate: Blainville's beaked whale)		400 (surrogate: Blainville's beaked whale)
Meosplodon hectori	Hector's beaked whale	60 (surrogate: Blainville's beaked whale)	[<800[d]]	240
Mesoplodon layardii	Strap-toothed whale	170 (surrogate: Sowerby's beaked whale)	>1300[b]	390
Mesoplodon mirus	True's beaked whale	136[d]	>1020 (M)[a], 1400 (F)[a]	510
Mesoplodon perrini	Perrin's beaked whale	60 (surrogate: Blainville's beaked whale)		400
Mesoplodon peruvianus	Pygmy beaked whale	49 (surrogate: Gervais' beaked whale)		240
Mesoplodon stejnegeri	Stejneger's beaked whale	80[b]	1600[b]	480
Tasmacetus shepherdi	Shepherd's beaked whale	170 (surrogate: Sowerby's beaked whale)		390 (surrogate: Sowerby's beaked whale)
Ziphius cavirostris	Cuvier's beaked whale	250[a]	2600 (M)[a], 3000 (F)[a]	1300
Carnivores				
Family Mustelidae				
Enhydra lutris	Sea otter	2[a]	45 (M)[a], 33 (F)[a]	16
Family Phocidae				
Cystophora cristata	Hooded seal	22[a, w, x, nn]	400 (M)[a], 300 (F)[a] [192-352 (M)[b], 145-300 (F)[b]]	145
Erignathus barbatus	Bearded seal	29[m, y, oo, pp, qq]	260 (M)[a], 425 (F)[c] [250-300[c]]	130
Halichoerus grypus	Gray seal	13[n, z, rr, ss, tt, uu, vv, ww]	400 (M)[c], 250 (F)[c] [170-310 (M)[b], 105-186 (F)[b]]	105
Histriophoca fasciata	Ribbon seal	22[kk, ll]	90[b]-148[b] [72 – 90[c]]	72
Mirounga angustirostris	Northern elephant seal	88[mm]	2500 (M)[b], 710 (F)[b] [2000(M)-600(F)[1]]	355
Monachus schauinslandi	Hawaiian monk seal	50[aa, bb]	230 (M)[a], 270 (F)[a] [170 – 240[c]]	165
Pagophilus groenlandicus	Harp seal	18[b, z, cc, dd, ee]	140 (M)[a], 130 (F)[a] [135 (M)[b], 120 (F)[b]]	65
Phoca vitulina	Harbor seal	8[b, ff, ll]	170 (M)[a], 130 (F)[a] [70-150 (M)[b], 60-110 (F)[b]]	60
Pusa hispida	Ringed seal	20[y]	110[a] [50-70[b]]	50
Phoca largha	Spotted seal	20[gg]	130[a] [82-123[b]]	82

Species Name	Common Name	Calf / Pup Mass (kg)[1]	Adult Mass - Maximum [Typical Range][2]	Representative Adult Mass (kg)[2]
Family Otariidae				
Arctocephalus townsendi	Guadalupe fur seal	13[hh]	220 (M)[a], 55 (F)[a] 160-170(M)[b], 40-50(F)[b]	27
Callorhinus ursinus	Northern fur seal	12[ii]	270 (M)[a,b], 60 (F)[a] [200-250 (M)[c], 45 (F)[c]]	30
Eumetopias jubatus	Steller sea lion	40[jj]	1100 (M)[a], 350 (F)[a] [566-1000 (M)[b,c], 263-273 (F)[b,c]]	175
Zalophus californianus	California sea lion	15[kk]	390 (M)[a,1,b], 110 (F)[a,1,b] [350 (M)[c], 100 (F)[c]]	55
Sirenians				
Family Dugonginae				
Dugong dugong	Dugong	20[b]	400[b]	120
Family Trichechidae				
Trichechus manatus	West Indian manatee	27[o]	1590[b]	477
Sea Turtles				
Family Cheloniidae				
Caretta caretta	Loggerhead turtle	8.7[p]	[70 – 170][v]	70[y]
Chelonia mydas	Green turtle	8.7[q]	395[v] [110 – 190][v]	110[y]
Eretmochelys imbricata	Hawksbill turtle	7.4[r]	[46 – 70][v]	46[y]
Lepidochelys kempii	Kemp's ridley turtle	6.25[s]	[32 – 49][v]	32[y]
Lepidochelys olivacea	Olive ridley turtle	7.15[t]	[35 - 45][v]	35[y]
Family Dermochelyidae				
Dermochelys coriacea	Leatherback turtle	35.18[u]	916[v] [300 – 500][v]	300[y]

[1] Where the literature provides a range of sizes, the lowest value is shown. For cetaceans, sirenians, and some carnivores (Mustelidae, bearded and gray seals within Phocidae), newborn masses are provided. For the remaining carnivores, the pup mass is the lowest estimated mass that the pup enters the water. For sea turtles, pelagic juvenile (approx. 2-yr) masses are provided.

[2] Maximum, typical, and sex-specific adult mass values provided when available. Representative adult mass is a reasonable estimate of a low adult mass for a species. For sexually dimorphic species, mass of the smaller sex is assumed. Because information available for species is variable, the following were followed to estimate representative adult mass:

1. Lowest end of adult range, if a reasonable representative range is available OR lowest end of reasonable adult range of smallest sex
2. If the above is not available, either (in order applied):
    a. 50 % of maximum mass of smallest sex
    b. 30% of maximum overall mass or maximum largest sex mass
    c. Mass at maturity
    d. Surrogate species

Species Name	Common Name	Calf / Pup Mass (kg)[1]	Adult Mass - Maximum [Typical Range][2]	Representative Adult Mass (kg)[2]

[a] (Reeves et al., 2002)

[b] (Jefferson et al., 2008)

[c] (Perrin et al., 2002)

[d] Reidenberg and Laitman (2009) in (Perrin et al., 2009)

[e] Mann et al. (2000)

[f] (Gambell, 1985)

[g] (Westgate & Read, 2006)

[h] (Nachtigall et al., 2005)

[i] (Heise, 1997)

[j] (Plon, 2004)

[k] (Ferrero & Walker, 1999)

[l] (Dalebout et al., 2003)

[m] (Lydersen et al., 2002)

[n] (Iverson et al., 1993)

[o] (Caldwell & Caldwell, 1985)

[p] (Southwood et al., 2007)

[q] (Wood & Wood, 1993)

[r] (Okuyama et al., 2010)

[s] (McVey & Wibbles, 1984) and (Caillouet et al., 1986)

[t] (Rajagopalan et al., 1984)

[u] (Jones, 2009)

[v] Sea Turtle Conservancy https://conserveturtle.org (2015)

[w] (Kovacs & Lavigne, 1992)

[x] (Lydersen et al., 1997)

[y] (Lydersen & Kovacs, 1999)

[z] (Kovacs, 1987)

[aa] (Kenyon, 1981)

[bb] (Antonelis et al., 2003)

[cc] (Kovacs & Lavigne, 1985)

[dd] (Kovacs et al., 1991)

[ee] (Lydersen & Kovacs, 1996)

[ff] (Drescher, 1979)

[gg] (Boveng et al., 2009)

[hh] (Gallo-Reynoso & Figueroa-Carranza, 2010)

[ii] (Testa, 2012)

[jj] (Loughlin, 2009)

[kk] (Tikhomirov, 1971)

[ll] (Burns, 1981)

[mm] (Reiter et al., 1978)

[nn] (Bowen et al., 1985)

[oo] (Andersen et al., 1999)

[pp] (Kovacs, 2002)

[qq] (Lydersen et al., 1994)

[rr] (Bonner, 1981)

[ss] (Iverson et al., 1993)

[tt] (Mellish et al., 1999)

[uu] (Haller et al., 1996)

[vv] (Bowen et al., 2007)

[ww] (Noren et al., 2008)

[xx] (Newsome et al., 2006)

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